F.E.ALLISON

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DEVELOPMENTS IN SOIL SCIENCE 3

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BY

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PREFACE

Soil organic matter has, since the dawn of history, been the key to soil fertility and productivity. In the earlier years, as nomadic populations moved about in search of places where they could settle down and till the soil, they selected the soils that were most productive, and this meant highest in organic matter, even though they may not have recognized this fact. They knew almost nothing about soil organic matter, or how it functioned, but they reaped the benefits of it.

In recent years scientists have determined with considerable exactitude the reasons for the benefits commonly realized from soil organic matter. These are discussed in some detail on the pages that follow. It will be noted that organic matter plays major roles in the chemical, microbiological and physical aspects of soil fertility. Some of these effects are so hidden and intangible as to be almost ignored and greatly underevaluated by those who are not specialists in the separate scientific branches. The role of soil organic matter as a source of nutrients, primarily nitrogen, is the one phase of the subject that has been most emphasized, but, as brought out on the following pages, it is only one of the important factors. Because of this overemphasis on nutrient source there has been a tendency in the present fertilizer era to place less emphasis on soil organic matter as a factor in plant nutrition. The present availability of abundant commercial nitrogen does not, however, make soil organic matter any the less valuable; nitrogen acts as a supplement and is, in fact, the most important constituent of humus. The addition of nitrogen fertilizer makes it much easier to maintain humus at the desired level, thereby making it possible to obtain more benefits from it.

In most previous extended discussions of soil organic matter it has been customary to put the major emphasis on the chemical nature of the final product, humus. In the present book I have chosen not to follow this practice, but rather to emphasize the dynamic nature of soil organic matter, which it seems to me is of far greater importance than knowledge of the exact nature of the organic constituents in humus. The transformations involved in the decomposition of plant and animal residues are brought about almost entirely by biological agencies, primarily microorganisms and to a lesser extent soil fauna. In fact, humus itself is a colloidal amorphous material containing many living and dead bacteria. Microorganisms and their products play important roles in soils, including their genesis, tilth, nutrient release and retention, erosion control and productivity. It has been necessary, therefore, to give considerable attention to their nature and activities as they relate to organic matter decomposition. When one considers that, in nature, soil organic matter and microorganisms are inseparable, it follows that a discussion of one apart from the other is virtually impossible, and even undesirable.

In the preparation of the various chapters that follow, every effort has been made to present the subject matter in terms that are easily understood by those with limited scientific training. All technical terms could not, of course, be avoided. The term soil organic matter is used in the broadest sense to include everything from newly-added materials to the thoroughly decomposed and polymerized residual matter that we designate as humus. In the text the two terms are sometimes used together, or interchangeably, because there is no sharp line of demarcation between humus and the remainder of the organic matter.

Numerous citations and quotations from the literature are given, that it is hoped will be of value to those who wish to further investigate the subject. Where the results of such research are discussed, the author has chosen to use the same units of weights and measures reported by the various investigators. The conversion of all values into the metric system, as might have been advisable, would have necessitated the use of many fractions that I considered more objectionable than the practice followed.

The author wishes to acknowledge the help, suggestions, and encouragement of his colleagues offered before and during the time that this book was in preparation. He is especially indebted to J.O. Legg, C.W. Carlson, Frank G. Viets Jr. and W.A. Raney of the Division of Soil and Water Conservation, U.S. Department of Agriculture, where he spent many pleasant and profitable years. He is also indebted to the many authors who so kindly gave their permission for the use of material that is reproduced here either in the text or in the form of graphs and tables.

Special acknowledgement is made to the many publishers who cooperated in this endeavor by granting permission to reproduce copyrighted material. Space does not permit naming all of the publishers individually here; however, proper recognition is given in appropriate reference sections at the end of the chapters.

F.E. ALLISON

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Chapter 1

SOME AGRICULTURAL PRACTICES OVER THE CENTURIES

INTRODUCTION

Soil organic matter has over the centuries been considered by many as an elixir of life – in this case of plant life. Ever since the dawn of history, some eight thousand or more years ago, man has appreciated the fact that dark soils, commonly found chiefly in the river valleys and broad level plains, are usually (but not always) productive soils. He also realized at a very early date that color and productivity are commonly associated with organic matter derived chiefly from decaying plant materials.

In the early years, when this world was sparsely populated and agricultural science was essentially nonexistent, man was accustomed to lead a nomadic existence. At first he depended chiefly or wholly for food on wild animals that he could kill; on fish and other creatures from the streams, lakes and oceans; and on whatever products of the forests and grasslands he found edible. But he soon found that it was often to his advantage to settle down and raise at least a portion of his food. This beginning of agriculture did not always put an end to his nomadic existence, for often he moved about in search of better places to practice his husbandry. Such moves may have been in search of water, a warmer climate, to escape hostile neighbors or pests, and for many other reasons, not the least of which was a more productive soil. As world populations increased and nations became established with more or less fixed political boundaries, nomadic life was for the most part no longer possible.

Man also learned at an early date that in many, or most regions, even the most productive soils may gradually become less productive. Among the reasons for this are erosion, heavy cropping, inadequate water or improper management of it, excess acidity, accumulations of alkali, and many others. Ever since man first experienced decreases in soil productivity he has waged a constant warfare against the degrading agents in his attempts to maintain or increase the productivity of his soils. In most of these efforts organic matter from various sources played a key role and contributed to his success. It seems profitable, therefore, preliminary to consideration of the main topic of this book, to take a few glimpses at history to see how the problems of maintaining soil productivity and securing adequate crop yields have been met by peoples living in different environments with respect to soils and climate.

For those interested in the broad aspects of man's conquest of nature, and his step-by-step progress in arriving at our present industrial status, reference should be made to the book by Forbes (1969). The rapid progress during the past century contrasts sharply with the comparatively slow developments over the earlier centuries.

AGRICULTURAL PRACTICES IN THE ORIENT

Among the oldest agricultural countries are those in the Orient, especially China and India. These have long been the most densely populated countries. How have these and other oriental countries been able to supply food to their people over a period of at least 40 or 50 centuries without the importation of appreciable amounts of either food or fertilizers? Published literature that gives the essential details of their agricultural system in the early years of their history is scarce. King (1911) has, however, supplied us with much information based on his travels in Japan, China and Korea just prior to his death in 1911. As he emphasized, there is every reason to believe that the farming practices that he observed in the early years of this century had not changed appreciably for many centuries. Let us take a look at some of his observations with the emphasis chiefly on China.

Livestock

The animal populations of the countries of the Orient have consisted chiefly of water buffaloes, donkeys, pigs, chickens, sheep, goats, cattle and some horses. Water buffaloes and donkeys have been used as draft animals. Cattle are comparatively scarce except in India where they are commonly considered as sacred animals, and hence not to be used for meat. In China and elsewhere pigs and chickens are fairly abundant, and sheep and goats are likely to be found where there are waste lands suitable for grazing. Farther north in Manchuria horses are common.

The people of the Orient are for the most part vegetarians, and necessarily so. Raising livestock for meat is usually a wasteful process compared to direct human consumption of the products of the farm and garden. In most of these lands, however, it is a common practice for each home in agricultural areas to have one or two pigs that exist chiefly on wastes of the home. Chickens are even more plentiful and the eggs furnish a much needed supplement to their main diet of rice and vegetables. Goat milk also serves as a minor food source and fish are utilized to the extent that they are available.

Soils

Most of the crops of the Orient are grown on delta and overflow lands, or at least on soils that were formed in this manner. This is particularly true in China and Indonesia. In China the rivers have carried so much silt and deposited it on the deltas that much new land has been built up over the ages. Flood plains and valley soils are deep and fertile soils that are capable of producing large crops for many years, but not indefinitely without return of plant nutrients. Farming practices developed by the Orientals that have made possible a permanent agriculture on these soils are discussed in the following pages.

The percentage of the total area of some of these oriental countries that is cultivated is often less than is generally realized. We usually think of Japan, for example, as being a country with an extremely intensive agricultural system where every square foot of soil is utilized to its fullest extent. This is true, but Japan is a rugged country where the cultivable land area is not large. According to King, only 14% of the land area was under cultivation at the time of his visit. Some of the hilly areas have been reclaimed and put under cultivation since that time, but spreading cities have doubtless removed from cultivation some of the better agricultural acres.

Japan is a scenic country, both because of its natural beauty and intensive agriculture and also because it is a land of rice paddies. Most of the hillsides along the river valleys are terraced if the slope is not more than about 15 degrees. In some places it would take several of these paddies to make an acre of usable soil. In China and elsewhere in the Orient many farmers over the centuries have gone to great effort to level the soil if not naturally level. Of course this is not a major problem in delta areas, but as agriculture has been extended up the slopes the work involved has been tremendous.

Lowdermilk (1953) and many others have emphasized the tremendous amounts of silt that have been carried by the rivers of China. This soil has been derived largely from the regions where there was no terracing or other protection against erosion. Lowdermilk states that millions of acres have been made almost worthless as a result of gully formation in the deep, and once fertile, loessial soils of northern China. The need for fuel and pasturage has been so great over the centuries that the hilly lands have been largely denuded, and erosion has removed most of the soil, leaving gullies, bare rocks, or in some regions, deserts. Fortunately, in at least some hilly regions the Chinese have kept erosion to a minimum by maintenance of vegetation of some kind, usually grass or trees, on the soil at all times.

Soils of the Orient, like those elsewhere, vary from heavy clays to rocky formations with all gradations in between. The areas that produce most of their field and vegetable crops are largely silts with considerable clay and sand. In general, the texture, structure and tilth of these soils seem not to have presented insurmountable problems in their agricultural use. Doubtless this can be attributed in large part to the extreme efforts over the years to add each year as much organic matter as possible.

In the rice paddies of Japan, according to King, the soil was usually plowed to a depth of 3.5–4.5 inches but in China it was worked deep and often – much of it by hand labor. Apparently extreme efforts were made in China to maintain a soil- or dust-mulch, except, of course, where rice was grown. One can not help but wonder how such a laborious practice could have been followed over the centuries if it is without merit, as has been shown by scientists in recent years. Certainly it has some merit with respect to weed control, mineral availability, and soil aeration, if not for moisture conservation.

Crops

In most of the Orient the climate is so mild that two or three crops are grown each year. Where as many as three crops are grown it is usually necessary to practice intercropping; that is, the planting of a second crop before the other matures. This is made possible by the common practice of hill and row culture, even for some of the small grain crops.

The field crops vary somewhat with country and climate but consist for the most part of rice, wheat, barley, millet, soybeans and peanut. Rice is the main bread crop of most of the Orient but farther north millet and sorghum assume first importance.

Vegetable crops include nearly all that are grown in the West and several additional ones. A considerable portion of the diet of the Chinese consists of the tender portions of various plants, including bamboo shoots.

Fruit trees of various kinds are grown throughout the Orient. These are commonly grown as dwarfs or trained to a trellis. Mulberry trees, grown even in the delta lands, serve as food for the silkworm. Tea bushes cover many hillsides in various regions. Forest trees are common on the more hilly or mountainous soils but are often harvested periodically for fuel and other purposes. Grass and weeds occupy other areas and serve as food for sheep, goats, cattle and other animals. Nothing is wasted.

Fertilizing and mulching

The key to the maintenance of a permanent agriculture over the centuries in the Orient has been the addition to the soil of every possible material that the farmer considered would contribute nutrients to his crops. Such materials consisted chiefly of various kinds of organic matter, including human and animal manures, crop residues, canal muck, and vegetation from hill lands and canals. All ashes were saved and returned to the land directly or indirectly.

Legume crops, including clovers, soybeans, peas, beans, lima beans, and others contributed much nitrogen from the air over the years, even though they may not have been used as green manures. Whether eaten by humans or animals, or turned under in their entirety, we know that under the oriental system of farming most of the nitrogen fixed by legumes gets back to the soil and helps to nourish the crops that follow. Actually, there is little evidence that green manuring, as we know it in the West, was followed extensively. Most any crop was considered too valuable to be turned under. Let it first serve as food for humans or livestock before being returned to the soil. In some regions it was common practice to grow a crop of clover after rice and in many cases this was turned into the soil.

Commercial fertilizers, as we know them, have been in existence even in the West for only a little over a century although small amounts of phosphates, potash and lime were used earlier in the West. In the Orient some fish fertilizers, and bean and peanut cake, were important and used but the quantities of these materials applied were never large. This meant that agriculture was on a self-sustaining basis in all of the oriental countries for centuries.

Composting was the channel by which many of the plant nutrients were prepared for application to the soil. Many of the waste plant materials were weedy with wide carbon–nitrogen ratios, and the oriental farmers learned early that such materials can be utilized most efficiently via the compost pile. Even most animal manures were not applied directly, but also first went into the compost pile. Wood ashes, canal muck, tree leaves, straw, water plants and anything else that was obtainable all found their way into the compost heap. In most cases thick layers of canal mud or grass sods were used to build up the compost heap. After a few months with interim stirring, decay had proceeded to where most woody materials had largely disintegrated and application could be made directly to the crops. This was done either before seeding or as a side dressing to the growing crops. In either case it was worked into the soil promptly, thereby assuring rapid and efficient utilization of all the nutrients. It is fortunate that the practice of adding comparatively large amounts of rich soil to the compost heap was followed. This served to absorb any ammonia produced and thus prevented large losses of nitrogen in gaseous form. Frequent stirring also provided aeration and thereby prevented large losses of nitrogen as free nitrogen gas that forms as a result of anaerobic decomposition of nitrites and nitrates.

The collection and distribution of night soil represented a very large amount of labor, and some expense, but this waste material contributed in a major way to their crop yields. It was sometimes added to the compost pile but more often it was diluted some 5-fold and added to the growing crops in the liquid form by means of a long-handled dipper.

Mulching was practiced to some extent, especially by the Japanese, where fruits and tea plants were grown, and also in vegetable gardens. Straw mulches placed between rows of vegetable or tea plants not only produced the usual beneficial physical effects but also served as a source of potash and minor amounts of other elements. All vegetable matter under oriental conditions was considered valuable and was used for a number of purposes, some of which were not agricultural. If such competition for it had not existed doubtless a much larger proportion of the plant residues would have been applied as mulches. The farmers certainly appreciated their agricultural value with respect to water infiltration, moisture retention, nutrient supply and last, but not least, soil organic matter maintenance.

AGRICULTURE IN BIBLICAL LANDS

Modern agriculture probably had its origin in Mesopotamia, although it is not possible to prove this conclusively from the present available evidence. Excavations made in this region during the past half-century have thrown considerable light on the people and their habits during the period beginning eight millenia prior to the time of Christ. From this starting point, the early knowledge spread throughout the Middle East and eventually to all parts of the world.

In Mesopotamia through the reign of Hammurabi

A summary by Hole (1966) shows that between 8000 and 3000 B. C. human society developed from self-sufficient bands of nomadic hunters to economically and probably politically integrated city dwellers who became specialized in various occupations. He states that the Mesopotamian civilization that began at least a few centuries before 3000 B. C. was characterized by temples, urban centers, markets, art, trade, writing, special crafts and militarism. Archeological evidence indicates that these people early developed a stratified society with adequate facilities for the regulation of production and distribution of resources, even if on a comparatively small scale.

Agriculture in this period of 8000–3000 B.C. was limited to the alluvial plain near the Persian Gulf and to the mountain valleys above. Hole states that the records indicate that barley, wheat and dates were raised and that sheep, goats, cattle and pigs were kept. Fish, fowl and probably a variety of vegetables were also a part of the diet of these early civilizations. Crops and livestock were grown in a limited way as early as 8000 B.C. even though the societies then were small, self-sufficient and showed little differentiation with respect to occupation or status. Only the best agricultural land was used initially but as populations increased, irrigation was introduced on some of the drier, but fertile, soils. This necessarily involved community action by many persons farming a number of acres. Insufficient fertility seems not to have been a major problem although MacKay (1950) states that manures were used here prior to 2000 B. C. The growing of leguminous crops, including vetches, alfalfa, and peas, dates back to early historic times in Mesopotamia.

The Bible contributes much information on agricultural practices in the Holy Land and in nearby countries of the Middle East during the time of Abraham (Abram), beginning about 1900 B. C. and extending through the first century of the Christian era. There are of course no long detailed discourses on agriculture but very meaningful pieces of information are given throughout both the Old and New Testaments that show very clearly how these peoples obtained their food supplies by the raising of livestock, field crops, vegetables, and tree and vine crops. Few people, even though students of the Bible, seem to realize fully how comparatively advanced agriculture was in some of these regions as early as 4000 years ago. This information has been assembled in a very complete and interesting form by MacKay (1950).

In *Genesis* 9, 20 it is stated that immediately after the flood (about 2450 B. C.) "Noah began to be a husbandman, and he planted a vineyard". Before him, Adam was placed in the Garden of Eden and told to "dress it and keep it" (*Genesis* 2, 15). Adam, Cain and Noah were cultivators of the soil rather than shepherds. The location of the Garden of Eden is not known but it is generally believed that it was in Mesopotamia in the lower valleys of the Tigris and Euphrates rivers. Regardless of how literally one accepts the Biblical stories of man's origin and early existence, the fact remains that these Biblical accounts so far as they relate to agriculture are in close agreement with the facts gained in recent years by archeologists.

There is evidence from the Bible and other sources that at the time of Abraham's birth in Ur of Chaldes (Mesopotamia), civilization had reached a rather advanced stage. Speiser (1964) states that during the reign of Hammurabi (18th century B. C.) "Mesopotamian civilization was cosmopolitan, progressive and sophisticated. A common heritage of law and government, which was stabilized by the use of the same script and international language, served to safeguard social gains and facilitate relations among the various states of the land. Writing was ubiquitous, not only as the medium of law, administration and business, but also as a vehicle for literary and scientific endeavours. In addition to law, outstanding advances had been achieved in linguistics, mathematics and the study of history. Architecture and the arts flourished, agriculture and animal husbandry were highly developed and far-flung commercial enterprises added to the material prosperity. (Indeed, on most of these counts, the classical lands of a thousand years later appear primitive by comparison.) In short, the Mesopotamia of Hammurabi and his neighbors was the most advanced land in the world – a vigorous force at home and a magnet to other countries near and far."

Abraham lived in this advanced civilization of Mesopotamia until he was 75 years of age (*Genesis* 12, 4) and then, on orders of God, he left for the land of Canaan. It is logical to assume that he carried with him much of the know-how that he had learned during 75 years in this agriculturally advanced civilization. In this connection, MacKay states that "Sumerian records, dating back to 3500 B. C., depict wooden plows, some oxen-drawn and some man-hauled. The Accadians superseded the Sumerians in this area, and their agricultural records, still preserved, advised plowing, raking, and manuring in the preparation of a seedbed. The tenth verse of the tenth chapter of Genesis tells of Babel and Accad, cities which gave their names to Babylonia and Accadia: Abram, brought up in this advanced civilization, must have been familiar with the requirements of good agriculture. Isaac's wife, Rebekah, came from the same Mesopotamian district, while Jacob spent twenty years with relatives there. Egyptian records, contemporary with the farming tablets of Accadia and early Babylonia, are blank insofar as agriculture is concerned. Perhaps the reason why Abram was welcomed in Egypt (*Genesis* 12, 16) was because of his skilled plant lore, as well as for his pretty wife. Joseph, Jacob's favorite son, may have absorbed grain-growing techniques from his fathers, and put them to good use in Egypt when the opportunity presented itself." One can only wonder how much, if any, exchange of agricultural information occurred between the early civilizations of the Far East and that of Mesopotamia. Their agricultural systems differed markedly but much of the difference could logically be attributed to the differences in soils, crops, and climate. If these peoples were in contact it seems probable that the Orientals learned more agriculture from the Mesopotamian farmers than the reverse.

In Egypt before the exodus

The Egyptians seem to have had a well-developed agriculture dating back to the first days of recorded history. Fred et al. (1932) state that the seeds of Leguminosae formed an important part of the food supply and also entered into religious and burial services. The legumes are believed to include beans, lentils, chick pea and possibly bitter vetch. Their main food crops, however, were the various small grains.

The children of Israel dwelt in Egypt for 430 years (*Exodus* 12, 40), until somewhere near the middle of the thirteenth century B.C. When the exodus began there were "about six hundred thousand on foot that were men, besides children. And a mixed multitude went up also with them; and flocks, and herds, even very much cattle" (*Exodus* 12, 37–38). During the 430 years the Israelites had grown from a very small group to a nation of considerable size for those times. It was probably this size and competition with the native Egyptians that led to much friction and eventual mass exodus.

The Israelites had settled in the Land of Goshen which was probably in the northeastern delta of the Nile river. This was a fertile region and productivity was doubtless maintained at a high level by the frequent flooding that was characteristic of the Nile valley. The new immigrants had been accustomed to a nomadic shepherd type of life before going to Egypt but the native Egyptians preferred cattle, although they raised sheep, goats, gazelles and pigs. They were also cultivators of the soil in a major way. Their crops included almost all of the small grains, vegetables, fruits, legumes, and flowers that we now commonly grow in the United States, except of course potatoes, maize, peanuts and tobacco. Irrigation and flood control were practiced. The production of small grains, particularly wheat, seemed to have been impressive although we do not know the yields per acre. Certainly, the total production was at times very great, for during the seven years of plenty prior to the seven years of famine in Egypt (about 1700 B. C.), when Joseph was in charge of agricultural production, it is stated that he "gathered corn as the sand of the sea, very much, until he left numbering; for it was without number" (*Genesis* 41, 49). It is stated further in verse 57 that "all countries came into Egypt to Joseph for to buy corn; because that the famine was so sore in all lands."

We learn from the 47th chapter of *Genesis* that the land was owned by the king and rented out to the farmers. Farming was conducted under a system of regimentation not unlike the feudal system of Europe at a much later date. We gain the impression that the Israelites developed from nomadic sheep herders to successful settled farmers during their stay in Egypt.

According to MacKay the fruits grown included apples, pears, peaches, apricots, cherries, melons, olives, figs, lemons and pomegranates. Among the vegetables were peas, beans, asparagus, cabbage, celery, cucumbers, leeks, onions, radishes, melons, cress and garlic. Both cotton and flax were grown; cotton cloth was common, whereas linen was prized and expensive. Flowering plants included roses, chrysanthemums, lilies, oleanders, lotus, narcissus, poppies and cornflowers.

In the Promised Land, 1200 B. C. to 100 A. D.

When the Israelites migrated from Egypt to Canaan they were much more efficient in agriculture than at the time of Jacob and Moses. The main interest of many of them had been in animal husbandry but as a result of their experience in Egypt they were now much interested in diversified agriculture. The various tribes settled in assigned regions, and nomadic life essentially came to an end; the growing of grain, fruit, vegetables, and herbs now became the common practice. Vineyards and wine production were emphasized, and date culture was a leading agricultural industry. Nut trees, such as the almond, pistachio and walnut are mentioned. The people whom the Israelites displaced in the Promised Land seem to have practiced a rather permanent system of agriculture. The men whom Moses sent into Canaan as spies returned with the news that it was a land of walled and very great cities, and flowing with milk and honey. In *Numbers* 13, 23 it is stated that the spies "came into the valley of Eschol, and cut down from thence a branch with one cluster of grapes, and they bare it between two upon a staff; and they brought of the pomegranates, and of the figs."

Allowing for some exaggeration or over-enthusiasm, there is still no doubt that Canaan had a well-developed agriculture at the time. When the Hebrews moved in they apparently followed much the same pattern and introduced some additional practices that they had learned in Egypt.

At the time of Solomon (about 1000 B. C.), grain growing must have been practiced on a comparatively big scale for when Solomon arranged for obtaining cedars of Lebanon for the building of the temple he agreed to pay Hiram, king of Tyre, large amounts of wheat and barley and also wine and olive oil (*II Chronicles* 2, 10). Wheat is mentioned several times in the New Testament and one gathers the impression that it was a common crop then and probably had been since prior to the time of Solomon. Incidentally, Solomon had "forty thousand stalls of horses for his chariots" (*I Kings* 4, 26). These animals alone must have consumed a lot of some kind of cereal.

The Israelites were constantly engaged in wars with surrounding tribes or nations, and their lives were also much influenced by merchants and others who passed through their country from the east and south, and later from Greece and Rome. Their exile in Babylon was short but must also have had a considerable effect since the peoples of this region were known for their special skills, already mentioned. The art of grafting may have been learned from them; at least they practiced it regularly in the time of Christ. The hanging gardens of Babylon were very famous but they may not have been gardens as we know them now. They were probably terraced hillsides. In Biblical times a garden usually was more likely to be a cool shady spot with a brook or fountain, rather than masses of annuals and perennials with banks of shrubs on the borders that we think of as a garden.

The New Testament writings do not indicate that any marked progress had been made in agriculture in the Holy Land during the ten centuries prior to Christ. Although foreign contacts had produced some changes, the overall effect seems to have been backward instead of forward. At the time of Christ the old pastoral sheep-herding type of agriculture had again become prevalent in many localities. This is not surprising considering the afflictions that befell the Jewish nation, including the Babylonian captivity, frequent wars, soil erosion, poverty, and the poorly organized tribal system of living. There were, however, some farms or regions where the more advanced types of agriculture learned in Babylon and Egypt, or imported from Greece and Rome, still flourished. The present remains of wonderful irrigation systems serve to emphasize the past glories and later shortcomings.

Not much information is supplied by the Bible regarding the maintenance of soil organic matter and fertility in Palestine and adjoining countries. This omission is not serious, though, because the facts that we do know are adequate to answer most questions. The Biblical lands were at all times sparsely settled. Even at the time of the exodus, we would infer from *Exodus* 12, 37–38, that not more than two or three million Jews left Egypt. In other regions, and at other times, the population per unit area was probably much less.

The Jews also seemed to prefer animal husbandry to the growing of cultivated crops, and they moved about when they could in search of good grazing lands. Good pasture lands in the Holy Land were apparently adequate for the animal populations except in years of drought, which were all too frequent.

The soils of Palestine and the Nile river valley were for the most part fertile. Most of the agriculture that involved plowing, planting and cultivation was conducted in the river valleys. Repeated flooding insured adequate plant food in most cases. In addition animal manures were of course returned to the soil under a grazing system. In other types of agriculture the use of animal manures is mentioned a few times, as in *Luke* 13, 8, where Christ told the owner of a non-bearing fig tree to cut it down. His answer was "Lord let it alone this year also, till I shall dig about it, and dung it." Human manure may have been used to a limited extent but certainly not as in China. MacKay states that the use of manures was common in Mesopotamia long before the time of Abraham. The ancient Romans were adept in handling and storing manure, and green manuring and crop rotation were in common practice. Seaweed, ashes, bones and various plant and animal substances were sometimes applied to soil.

Fussell (1966) states that the Greeks and Romans recommended that the farmer dig a pit near the farm buildings into which all animal and human excreta, leaves, vegetable refuse and household wastes should be thrown. Pigeon and poultry dung were considered of unusual value. Soil was sometimes added, and the whole stirred from time to time according to later composting practices. The value of green manures, legumes and mulches was fully realized, and some marl was applied to the land. Turf, either burned or unburned, was occasionally used as a manure.

Cultivation of the soil, often mentioned in the Bible, was the standard practice in those times but it is likely that only a shallow surface was disturbed. The plows were probably made of wood, although in most cases the cutting point or edge was undoubtedly of metal. The Bronze Age began in Europe about 3500 B. C. but somewhat earlier in Asia and Egypt. The Iron Age began about 1000 B. C. in southern Europe and somewhat earlier in Asia and Egypt. Fussell (1966) states that copper and its alloys began to be used in Egypt about 3000 B. C., and bronze metallurgy became known in western Europe between 1850 and 1000 B. C. Iron was not in general use until about 800 B. C. According to a newspaper report, recent excavations in Iraq indicate that 7000 years ago the people of that region had tools of obsidian, polished glass, or of polished and chipped flint.

Ancient Egyptian plows, pictured by Fussell, seem to have been largely of the type later designated as the aratrum or ard plow. It consisted of a beam to which a handle was attached and to which the draft animals were hitched. These two parts were fixed in the sole or share beam, making the whole into what was sometimes called a crooked plow. There were several variants of this plow to fit the soil and the use for which it was needed. The usual design seems to have consisted of a sharp point that penetrated the soil leaving a shallow furrow, but sometimes the share was provided with two ears for covering seed. At a later date this type of plow was sometimes equipped with two wheels in front and sometimes with a coulter. Some illustrations show a share broadened into a shovel-like point, or widened into a cutting edge. This plow with many variations probably dated back into the Bronze Age and was used in Europe at least as late as the Middle Ages. It was common practice in many places to plow a field at least twice and crosswise, to kill weeds and to prepare a better seedbed. Both animals and man were used to pull the plow and at times considerable power was used. In *I Kings* 19, 19 it is stated that Elisha "was plowing with twelve yoke of oxen before him, and he with the twelfth." This would, indeed, seem to have been a major operation for the times and agricultural implements used. Fussell comments on this as follows: "In the light soil of Palestine it is hardly likely that twenty-four oxen would be necessary to haul a light plow of the kind then in use, but it would have been quite possible for twelve plough teams to be working in one area." He states further that the same pattern of light plow was still in use in the early nineteenth century.

There is considerable uncertainty as to when the harrow came into use but Fussell states that by the first century A. D. a harrow of some pattern was in existence. It was commonly made of wood fitted with either wooden or iron teeth. Various types of rakes, forks, spades and pickaxes were available for the preparation of the soil in gardens or rocky areas where the plow could not be used. A four-toothed fork or rake was used for the handling of manures, and pruning and grafting knives were also available.

According to MacKay the Phoenicians, who were neighbors of Israel on the north and west, are believed to have discovered terracing and contour farming. This practice enabled them to utilize their hilly soils, control erosion, and maintain soil moisture during dry spells. He states that "the terraced mountainsides where flourished the vineyards of Judah and Israel owed their pattern to the earlier developments of the Philistines, and had little in common with the viticultural methods of Egypt and Babylon." (Many Philistines were descendents of the Phoenicians.) Animal manure was doubtless the main source of added nutrients to these terraced fruit-growing areas.

In the Middle East in the 20th century

The condition of the soils, and hence of agriculture, in the Biblical lands is now a far cry from what it was when the spies sent by Moses reported that Canaan was a land of milk and honey. Lowdermilk (1953) tells the sad story in a striking manner. Erosion has removed most of the soil from millions of acres of land in the various countries of the Middle East. In general, throughout much or most of the area only the comparatively flat river valleys and a few terraced areas are now suitable for agriculture. The old land of milk and honey is largely a waste land. Only traces of the famed cedars of Lebanon are now in existence. Lowdermilk speaks of 100 dead cities or villages in Syria alone, and of a landscape of rocks and little soil. As the soils disappeared so did the inhabitants.

In Mesopotamia he observed the ruins of the ancient civilization, including the old irrigation system that was apparently made useless by the millions of tons of silt that clogged it. The soils of the valleys of the Tigris and Euphrates rivers are still fertile but too arid for use without an irrigation system. He states that at its zenith the population of Mesopotamia was probably between 17 and 25 millions. All of Iraq now has only about 4 millions, including nomadic peoples.

Fortunately conditions in the Nile valley of Egypt have remained suitable for cropping. Erosion has not been a serious problem there and flood irrigation has been the usual practice. The conditions seem to be much like those encountered in the flood plains of the rivers of China. Elsewhere in North Africa soil erosion has proceeded much as in the lands farther east.

Soil deterioration throughout the Middle East can, according to Lowdermilk, be attributed primarily to the struggle between the tent dweller or shepherd, and the house dweller or farmer. From time to time people from the deserts have "swept down as a wolf on the fold to raid the farmers' supplies of food. Raiders sacked and robbed and passed on. Often, they left destruction and carnage in their path, or they replaced farmer populations and became farmers themselves, only to be swept out by a later wave of hungry denizens of the desert." The nomads not only neglected terrace walls but let their goats strip the hillsides of nearly all vegetation. Erosion of the hillsides has in many regions continued without interruption for centuries. All too often, over the ages, a people skilled in agricultural knowledge has been replaced by those who had little knowledge or interest in soils and crops, and even less interest in what happens to the next generation.

AGRICULTURE IN EUROPE SINCE THE BEGINNING OF THE CHRISTIAN ERA

During the period extending from the time of Christ to the present, agriculture in Europe has passed from a comparatively primitive stage to the most advanced in the world's history. Most of the progress has occurred during the last century, corresponding with, and caused in large part by, the scientific age and industrial revolution. Some of the steps in this transformation merit review.

Early European agriculture

Country life and agriculture in Italy and the Mediterranean countries was in a comparatively advanced and prosperous state at the time when Rome ruled most of the world. Many of the ruling class, or nobles, owned villas and had many slaves to tend them. Fussell refers to Martial's description of one of these villas as follows: "It was surrounded by open spaces, groves of myrtles and so on. Quantities of wheat were grown, and numerous amphorae held the wine harvest. In a deep valley the bulls roared, and the calves tried out combat although without horns. The barnyard was peopled with fowl, geese, pheasants and partridges, cocks from Rhodes, and doves. Gluttonous pigs and gentle lambs were kept. There was a fish garden for pleasure. Honey was collected in leatherpots. Conical cheeses were made. Dormice, small goats and capons were kept, so a fine diet of vegetables, eggs, poultry, fruit, cheese and new wine was eaten and drunk." But of course the common people did not participate to any extent in this type of living. Most of the people outside of cities lived in small villages and on scattered farms. Much of their time was devoted to the herding of sheep since Italy is a rugged country. In the summer the flocks were pastured in the mountains and forests and then brought down to the lowlands in the winter. In later times even less ideal farming prevailed and more of a tenant type of farming became established.

Little is known about farming practices at this early date in western Europe but they were apparently at a less advanced stage than in Italy although the Roman influence had spread around the Mediterranean. We know that in France vine crops and small grain and root crops were grown widely. Doubtless many other crops, as well as livestock, were found on the small and isolated farms.

The general situation that existed in Europe at that time is summarized by Fussell as follows: "In spite of having no adequate description it is clear that farming had been practiced in northern and western Europe, and in the southern parts of Scandinavia long before the Romans reached the coastline of the North Sea or crossed the Channel to Britain. There had been plenty of contact between the northern peoples and Romans. Each must have taught the other. The Roman garrisons, though rationed by imports of grain from Britain to the Rhine upon occasion, and from the fens of eastern England to the north, were peasants, and they practiced farming on the frontiers in Europe, if not in England. The Germans must have observed their methods. Similarly, they must have observed how the Germans and other barbarians lived. It is probable that the Germanic tribes followed a system of wild grass husbandry, ploughing out an area for a crop or two, and then letting it fall down again, but it has been suggested that in the early centuries of our era their method was a 2-year, or possibly a 3-year rotation of permanent fields. The first would be a crop and fallow system; the second the medieval winter corn, spring corn, fallow rotation, but this is unlikely."

Livestock consisting of cattle, pigs and sheep were kept in the northern regions of Europe. Pigs constituted the main source of meat and both the cows and sheep furnished the milk, some of which was made into cheese. The Germanic tribes frequently invaded areas to the south and west, thereby disrupting agriculture for a time but many of the invaders merely settled down to live more or less peacefully with the natives. In addition to the disturbances caused by the invaders, there were sporadic outbreaks on a large scale of diseases of cattle and sheep. Two of these outbreaks occurred in the period 387–389 A. D. Probably plant diseases also took their toll but these are not mentioned. Life at that time must have been an ordeal and certainly not conducive to very much happiness. All of these human trials and tribulations led to the establishment of the feudal system, partly for personal protection but also because of economic necessity.

Feudal system

Farming in Europe during the Middle Ages was conducted largely according to the feudal system, where the land was owned by the lord, and the tenants who farmed it paid rent to their master. In some sections the monasteries were the chief land holders and farming was done by the tenants or the monks. Production from these large estates was often rather large but there was no attention given to techniques, and often extensive areas were left uncultivated because of low productivity or lack of workers.

The portion of the land not in forests, grasses or other permanent vegetation was commonly farmed according to a communal or open-field system. The tenant usually owned nothing. The rotation commonly consisted of a winter grain crop and then fallow. There was little or no variation in cropping over the years. The rotation was followed of necessity because the grains were so much needed for food, and under their exploiting system of agriculture they had found it necessary to rest the land every year or two. Usually only a few livestock were kept and hence the land received little benefit from manure.

Nye and Greenland (1960) call attention to Parain's description of the agricultural system in the temperate zone of western Europe during the Middle Ages. Parain states that "the two-course system had spread widely in Gaul and Britain, in the wake of the Roman legions, and perhaps even before their arrival. But in the poorer parts of these countries, and in all Germany, much more primitive systems of temporary cropping – on forest land, moorland, and especially on open grassland over which the forest had not spread – were normal in the fifth century, and had not been altogether got rid of at the close of the Middle Ages. Forest land was sometimes regularly cleared, sometimes occupied for a time only, after the wood had been burnt to fertilize it. Clearing began on the plains, in valleys, and on the great terraces of mountain slopes. But on steep slopes and in high places difficult of access, men were satisfied with the temporary cultivation of ground burnt over – as they still are in Corsica and in the forest of Ardenne. As a rule only one crop was taken off it, originally oats, only from the eighteenth century also rye. This clearance by burning was still practiced near Paris in the twelfth century and was widespread in the Alps as late as the eighteenth. . . . It involved no application of fertilizers; but it squandered precious natural wealth, and often turned forest land into increasingly unproductive moorland. . . Part of the land was tilled for a year or a few years; then it lay fallow for many, and was used for grazing." Parain also states that "every holding had one corner which never rested – the garden. But there fertilizers of all sorts were applied to an extent which was impossible on the whole cultivated area." Only in a few localities, such as Flanders, were sufficient cattle raised to provide an abundance of manure.

The Middle Ages farming system was a slow soil-depleting process, where not even legumes were grown to any great extent to supply nitrogen. A few legumes, such as peas, beans, lentils, and vetch were often grown in the gardens but not on large acreages. Although we have no actual data, it is safe to say that several centuries of this type of farming lowered the level of soil organic matter and essential plant nutrients. Soil acidity must also have created problems, but additions of marl and chalk were sometimes made, probably on a very limited scale. Soil structure may have deteriorated, and doubtless erosion was a factor on cultivated areas. Shallow plowing with grains broadcast and not cultivated, and with weedy fallows in between, would of course go far toward controlling erosion. In northern and western Europe torrential rains are infrequent. The removal of excess soil moisture was done by surface drainage since tile drains were not in use in feudal times. Grain yields are known to have been low, probably about 10 bushels of wheat per acre at the end of the medieval period. At times some forested areas were cleared in order to have more fertile soils as substitutes for depleted ones. This was a shifting culture type of agriculture now common in many tropical regions.

The contrast between agriculture under this medieval feudal system and that in Mesopotamia 3000 years earlier, or in Egypt and the Holy Land at the time of Moses and later, is striking. As Lowdermilk states, the introduction of new and agriculturally unskilled workers makes a big difference. To this we might add that the political and economic status of a nation also makes a difference. Under the feudal system, as in communist Russia today, the tillers of the land had little incentive to work hard or to improve their methods.

The extremely slow progress made in agriculture in Europe during the period following the decline of the Roman Empire through the medieval period and for another two centuries was due to a large number of reasons, in addition to the depressing effect of the feudal system. These included many wars and invasions, frequent disease epidemics that hit both the human and animal populations and many crops, scarcity of population with small village settlements and little opportunity for community action, lack of even a primitive manufacturing industry, and almost no sources of plant nutrients other than animal manures.

Fussell describes conditions during the Dark Ages (500–1000 A. D.) as follows: "Besides the troubles of the invasions causing disturbances and uncertainty, here and there more or less complete destruction of the Romano-Gallic villas and settlements, another disaster fell upon the world in the middle of the sixth century A. D. The animal population had been subject to continuous outbreaks of contagious disease – no doubt similar disease had afflicted suffering humanity. Plague was endemic, but not in the same degree as the outbreak in or about A. D. 542, which was as virulent as the better-known Black Death of the fourteenth century, and spread to the populations of the then known world. The deaths have been estimated to have been of equal proportions. From Wales to Central Asia one-third to one-half the people perished. It is little wonder that in these circumstances the living tended to draw together into groups of a self-sufficient kind, if by no means of equality of status."

Plant diseases doubtless took their toll more or less continuously. Two of these epidemics that have occurred in recent years were the infection by *Phytophthora infestans*, which wiped out the potato crop in Ireland in 1845, and the fungus disease *Peronospora* that attacked grapes in France about 1878 to 1885. When one considers that no satisfactory remedies or cures for any of the diseases of plants, animals or man were known prior to the early part of the nineteenth century it is obvious that man lived a precarious life during this early period. Agricultural or industrial progress could scarcely be expected from people who must struggle just to live.

Individual tenure and mixed farming

A new era in European agriculture was reached near the end of the medieval period when the feudal manor system disappeared. Its end was greatly hastened by the Black Death with the accompanying high death toll that resulted in a scarcity of labor and the opening up of many opportunities for private initiative on the part of those who had previously been near-slaves of their landlords. Open-field agriculture gradually came to an end in many localities as the land came into private ownership. Some of it, especially in England, was enclosed and sowed to grass for the raising of sheep to meet the demand for wool. In a sense this was the beginning of modern agriculture because grass meant more soil organic matter and better soil structure, and less loss of fertility from the soils. Under this system soil depletion was essentially stopped but unless additions of nutrients were made from outside sources there could be no building up of fertility. The percentage of the arable land that was enclosed as early as the 15th and 16th centuries is not known but was probably small. The trend, once started, gained momentum with time.

Private ownership of the land meant that the farmer could do as he pleased with it. As economic conditions changed, his use of the land also changed. Mixed farming was a natural result; this usually meant that a portion of the farm was used for grazing and other portions for field and vegetable crops. The cropping system no longer had much in common with that of the old feudal system.

During the medieval period the raising of livestock had been limited because of the difficulty of keeping the animals alive during the winter months. This difficulty was partially overcome as a result of the introduction of new fodder crops at the close of this period, and the greater emphasis placed on legumes. Lupins, beans, vetch, peas and clover were now grown to some extent, often as catch crops. Leguminous crops, as well as root crops and other nonlegumes, were utilized mostly for feed but were occasionally used as green manures. It seems surprising that legumes, which were grown and highly valued by the Hebrews, Romans and Egyptians, should have been largely absent from the cropping systems of Europeans for centuries.

With land in private ownership, private initiative was stimulated and better cropping systems usually meant larger grain and forage yields and more manure from the livestock. With progress agriculturally and economically, and with the increase in population, more and more land was enclosed, particularly in England, not necessarily for the raising of livestock but for the raising of a wide variety of crops as demands developed. Landlords and tenants still existed but the relationship bore no close resemblance to that existing under the feudal system.

Printing was invented during the fifteenth century and for the first time in world history it was possible for agricultural knowledge to be easily and widely disseminated. Of course this did not happen immediately, but nevertheless comparatively rapidly during the following one or two centuries. Prior to this only handwritten books were available and these were found only in the libraries of monasteries and the great landowners.

Much of the agricultural revolution that began in the sixteenth century seems to have spread from Holland, Belgium, the lower Rhine country in Germany, and the surrounding areas (Fussell, 1966). This applies mostly to livestock breeding, but also to the growing of special crops and the use of mixed cropping systems. New breeds developed in the Low Countries soon became widely exported to other European countries, including England, and even to the United States. In many respects Holland can be considered the home of dairy farming. The climate and soil made this country a garden spot and the people took advantage of their inheritance. Nearby countries, however, were not many years behind them. Southern European countries, where the conditions for the raising of livestock were far less ideal, made progress in other directions, such as the growing of grapes, olives, rice, various fruits, and forage and fiber crops. Progress in all of these countries during this period was frequently slowed down by long wars, and by epidemics of human, animal and plant diseases.

For those who are interested in some of the details of the farming practices in the various western European countries during the 17th and 18th centuries, reference should be made to the discussion by Fussell. Marked progress was made during this period in nearly all phases of agriculture but space limitations do not permit their consideration here. During this period the Low Countries were the leaders in most respects, as they had been earlier. However, it was in Scotland about 1760 that the first factory was built for the production of the moldboard plow of the type known today. This new implement revolutionized tillage operations and greatly speeded up farming operations.

The era of chemical fertilizers

Agriculture as we know it today, which is based on the use of artificial fertilizers as sources of N, P, K and minor elements as supplement to nutrients supplied by the soil, began in a very limited fashion about the middle of the 19th century. It was the German chemist, Julius von Liebig, who in the period of about 1830–1840 began to apply his scientific knowledge to the study of plant and animal nutrition. By chemical analysis he determined the composition of plants and then gave consideration to how these needs could be supplied either by the soil or from outside sources. His early findings and theories stimulated others to do research in the same field. It was just after this that Lawes and Gilbert initiated both laboratory and field plot studies that led to the establishment of the Rothamsted Experimental Station at Harpenden, England. Agricultural research gained momentum, and the field of study broadened with time to include various biological sciences in the latter part of the 19th century. The 20th century has seen the rapid expansion of research into every possible phase of agriculture.

As knowledge increased, and likewise the demands for food by an expanding population, the use of chemical fertilizers also increased rapidly. At the time of Liebig the fertilizers used, other than animal manures, consisted chiefly of very limited amounts of ground bones, wood ashes and lime. Even composting was not practiced in a major way in western Europe. Legumes were being grown to some extent although the fact that bacteria living in the root nodules were essential for nitrogen fixation from the air was not known until Hellriegel and Wilfarth announced their findings in 1887–1888. During the early part of the 19th century some soils gained in fertility through the use of increasing amounts of animal manures, but any such increases usually meant that other soils decreased because the added manure nutrients were obtained from pastured soils. This began to change as the infant fertilizer industry began to develop. According to Fussell the first nitrate of soda was imported into Britain in 1839 and guano in 1840. The patent for the manufacture of superphosphate was taken out in 1842 and the mining of Stassfurt potash began in 1861.

Modern agriculture has now reached the stage where yields of 40–50 bushels of wheat per acre are fairly common, and yields of near 100 bushels have been recorded. This is quite in contrast to the 10-bushel yields in feudal times. Much of this tremendous change may be attributed to chemical fertilizers but of course not all of it. Better varieties, better drainage systems, improved soil structure, irrigation, erosion control, weed control, use of insecticides, and many other improved practices also share in the high yields now being realized, but it is probably safe to credit the use of artificial fertilizers as the most important of these factors under average farm conditions.

The abundant supply of commercial fertilizers has made possible the production of large crops on land that was once considered "worn out". It has also led to improved practices with regard to drainage, erosion control, and many other practices because fertilizers make it profitable to spend money on soils to put them in the best possible condition for high yields. Not all of the added fertilizer is removed by the first one or two crops but some of it remains fixed in the soil in a slowly available form. This applies particularly to phosphorus, much of which is chemically fixed in the soil; the same is true to a lesser extent of nitrogen and potassium. Heavy fertilization that results in large yields also commonly slowly increases the soil organic matter content if the soil was very low in it initially, and necessarily the nitrogen content of the soil. The result then is that fertilizers tend to increase soil fertility, or at least soil productivity.

Little more needs to be said about modern agriculture for we are living in the midst of it. More and more, in this age of food scarcities in many parts of the world, scientists are concerned with maximum feasible yields per acre in this era of chemical fertilizers. Fortunately there is no worthwhile evidence, contrary to the claims of the exponents of the organic gardening creed, that the use of fertilizers, insecticides, herbicides or other new materials or agricultural practices has (with minor exceptions) harmed either the soil, the farm products, the livestock, or the people living on the soil (see Chapter 28).

AGRICULTURE IN THE NEW WORLD

Early Indian agriculture

When Columbus, and later Spanish and Portuguese explorers, arrived in America they were impressed by the extent to which the natives were practicing agriculture. They were not savages, as is often supposed. According to Fred et al. (1932) the explorers observed extensive fields of corn, sweet potatoes, manioca and peanuts. The remains of Indian civilizations, still under intensive study, have also shown that the early Indian culture was more advanced than previously believed. Fred et al. state that "to the best of our present knowledge, the ancestors of the American Indians came to the Americas at some very remote time and lived here in complete isolation until the coming of Columbus. Perhaps they came from Asia across an ancient land bridge between Siberia and Alaska. The best evidence for this great antiquity of human history in the Western hemisphere is the fact of wide distribution and variation among the peoples and among the native plants which they had developed for their use. Such a process of adaptation must have taken many centuries; indeed some ethnologists venture the opinion that the early civilizations in America were contemporary with the very earliest of the Egyptians and the Sumerians and Akkadians of Mesopotamia, and perhaps of the Chinese and Aryans of northern India. However, that may be, we know that the great Maya civilization of Mexico, Yucatan, and Guatemala was well developed and making records and dates of its dynasties, written in stone, as early as 100 B. C. And the Megalithic Empire of the Pre-Inca people of the South American Andes began not later than 200 B. C. It was, of course, preceded by a half-legendary period of immigration and was followed, after a period of decadence, by the great Inca Empire."

Josephy Jr. (1969) gives an excellent description of the various Indian tribes in America, their cultures and extent to which they had advanced in government, the arts, and agriculture. At the time of Columbus' arrival, the Americas were a well-populated region; estimates of the Indian population in North and South America at that time vary between 8 and 80 millions. This is an appalling figure to most of us. Many of these Indians had a civilization and code of ethics that in many respects surpassed that of the Spaniards who conquered and eliminated masses of them in their greedy search for gold.

Indian agriculture was in some regions very advanced and elsewhere quite crude. It also varied with the climate over both North and South America. The Mayas and Pre-Incas cultivated miles of terraced hillsides and practiced irrigation. Among the legumes grown by the Indians were the peanut (a native of America) and several varieties of beans, including the lima bean.

Agriculture, as practiced by the American Indians at the time of the arrival of the European colonists, was far less advanced than that of the Incas and Mayas. However, they at least raised corn, beans, and peas in a limited way on small plots of ground.

Agriculture in the United States since colonial days

When the colonists arrived in the New World they brought with them the agricultural practices that were in use at the time in their homelands. As already stated, western Europe had by this time (17th and 18th centuries) passed into a period where better farms were enclosed and subjected to a system of mixed farming involving livestock and various types of crops as demand dictated.

In the New World these early settlers were with minor exceptions faced with unending miles of dense virgin forests; alluvial plains on the East Coast were almost nonexistent and the river valleys, like the rolling hills, were also densely wooded. Under these conditions the virgin soils yielded good crops for a few years without much attention to fertility. Doubtless the native Indian custom of burying a fish under each hill of corn was followed at times, but not as a common practice. With unlimited acres of virgin forests a form of shifting cultivation, now so common in many tropical regions, became the common practice. Any time that yields became unsatisfactory, or more land was needed to support the growing settlements, additional clearings were made. Much land was essentially abandoned for use in agriculture within a comparatively short time. This tendency was greatly accelerated as migration into the fertile Corn Belt area occurred. The 19th century saw the abandonment to forests of most of the lands of the East Coast that had once been under cultivation.

Shifting culture was even extended to some extent to the areas west of the Appalachian mountains, for much of this land was hilly and not well suited to agriculture after a limited period. Much of it in the southern edge of the Corn Belt, for example, was allowed to return to forests. Even in the beginning of the 20th century it was a common practice in some areas for a farmer to clear an acre or so for the planting of tobacco, corn, or other crop having high nutrient requirements. Livestock farming was a common practice from the early days, and the manure helped to maintain productivity, but this was inadequate. Erosion on a massive scale added to the farmer's woes and accelerated land abandonment and the shifting to less hilly and more fertile areas.

It was the introduction of artificial fertilizers toward the end of the 19th century and the beginning of the present one that gradually, but also comparatively rapidly, changed the whole agricultural outlook. Land that normally yielded 12–15 bushels of wheat or 25–40 bushels of corn per acre without commercial fertilizers would now yield two to four times these amounts when properly fertilized. As the population increased, demands for food and fiber also increased, and many acres once abandoned or nearly so were again put to use. Hybrid corn, improved varieties, and better farm management accounted in part for the increased yields but commercial fertilizers were the key to the transformation. Thousands of acres on the East Coast that were abandoned to forests have now been returned to productive agriculture. The same is true of large acreages in the South that were once used chiefly for cotton and corn culture.

Due credit for the agricultural transformation should also be given to the U. S. Soil Conservation Service movement that was initiated in this country about 1930 and rapidly gained momentum as the years passed. This organization was remarkably successful in getting the public consciousness awakened to the tremendous destructive forces of erosion and how to combat them. Fertilizers and erosion control went along hand in hand in helping to decrease the losses, and at the same time to bring into profitable production many acres that could not have been used satisfactorily without these additions to good soil management.

This brief sketch of agricultural developments in the United States shows that the country has followed closely along the lines initiated in Europe at an earlier date. Agriculture in the two continents differs somewhat, as would be expected, but is for the most part on a permanent basis. This permanent basis is however dependent on commercial fertilizers and is not permanent in the sense that Chinese agriculture was permanent for centuries. So long as the majority of the peoples of the world go to bed hungry, and populations continue to increase, the demands on agriculture will necessarily increase; fertilizers cannot be dispensed with as our organic farming adherents advocate.

REFERENCES

Forbes, R.J.,1969. *The Conquest of Nature.* New American Library, New York, N.Y., 136 pp.

Fred, E.B., Baldwin, I.L. and McCoy, E., 1932. Root nodule bacteria and leguminous plants. *Univ. Wisc. Stud. Sci.*, 5: 343 pp.

Fussell, G.E., 1966. *Farming Technique from Prehistoric to Modern Times.* Pergamon, New York, N.Y., 269 pp.

Hole, F., 1966. *Science*, 153: 605–611.

Josephy Jr., A.M., 1969. *The Indian Heritage of America.* Bantam, New York, N.Y., 397 pp.

King, F.H., 1911. *Farmers of Forty Centuries.* Democrat, Madison, Wisc., 438 pp.

Lowdermilk, W.C., 1953. Conquest of the land through 7,000 years. *U.S. Dep. Agric., Inf. Bull.*, 99: 30 pp.

MacKay, A.I., 1950. *Farming and Gardening in the Bible.* Rodale, Emmaus, Pa., 280 pp.

Nye, P.H. and Greenland, D.J., 1960. The soil under shifting cultivation. *Commonwealth Bur. Soils, Tech. Commun.*, 51: 156 pp.

Speiser, E.A., 1964. *Life*, 57: 39–41.

THE SOIL AND LIVING MATTER IN IT

Chapter 2

FORMATION AND CHARACTERISTICS OF MINERAL SOILS

DEFINITION OF SOIL

In starting this discussion of soil formation and characteristics, it seems pertinent first to define soil. This may seem unnecessary to many for we all are in daily contact with it and every farmer knows it as dirt; hence the term dirt farmer. Nevertheless the term soil does not convey the same meaning to all. Many definitions have been given but few, if any, are entirely satisfactory and all-inclusive.

In the glossary of the *1957 U.S. Yearbook of Agriculture*, entitled "Soil", three definitions are given, each being a little more involved than the preceding one. These are: (a) "The natural medium for the growth of land plants. (b) A dynamic natural body on the surface of the earth in which plants grow, composed of mineral and organic materials and living forms. (c) The collection of natural bodies occupying parts of the earth's surface that support plants and that have properties due to the integrated effect of climate and living matter acting upon parent material, as conditioned by relief over periods of time."

Webster's (1963) dictionary defines soil as "the loose surface material on the earth in which plants grow, usually consisting of disintegrated rock with an admixture of organic matter and soluble salts."

Jacks (1954), however, dislikes long definitions and states that "the longer they are the less they define and the more they describe." He defines soil very briefly as "what plants grow in." By this definition one would be forced to apply the name of soil to such diverse things as filter paper, glass beads, sawdust, bark, asbestos, vermiculite, and water, as well as to disintegrated rock, if plants grew in them – and they could. This definition is obviously unsatisfactory; the author prefers the one given in Webster's dictionary, but the three given by the United States Department of Agriculture are also good.

The nature of soil, the steps in its formation from parent rocks, the development of horizons, the role of living organisms and organic matter, and the effect of climate over the ages, are discussed in a popular manner by Simonson (1957). Since the major factors involved in soil formation vary from place to place and from time to time, the result is the formation of several soil groups consisting of many soil types with profiles that may be similar.

FORMATION OF SOIL

A knowledge of the agencies and forces involved in soil formation from the parent rocks, as well as the chemical and physical nature of the resulting soil, is necessary for a satisfactory understanding of the roles of living organisms and of decaying organic matter in crop production. It has been said that there is no soil without organic matter. Under natural conditions there is also no soil without microorganisms. Biological agencies are active in nearly every stage of soil formation. These agencies and their products, therefore, contribute substantially to the quality and characteristics of the final product. In the present book on soil organic matter it is essential that some attention be given both to soil genesis and to the contributions of living organisms to the final product, even though space limitations do not permit a thorough discussion of the subject.

The primary factors that are involved in the formation of soil and that determine its final characteristics are: (a) parent materials; (b) climate; (c) living organisms (plants, animals and microorganisms); (d) topography; and (e) time. Marked differences in any one of these factors is likely to have a major effect on the nature of the resulting soil. It is because each of these factors is so important and so interdependent that we have such widely varying types of soils.

The great importance of the kinds of rocks from which soils are formed is obvious since they are the primary source of the mineral nutrients on which plants will later feed. These rocks may be either igneous (solidified lava); sedimentary (deposited by water); eolian (deposited by wind); or metamorphic (formed when various kinds of rocks are subjected to high temperatures and pressures).

In the process of soil formation, these rocks undergo both physical and chemical weathering, which occurs most rapidly at or near the surface and progressively less at lower levels. The rate of weathering depends chiefly on the climate, mostly on rainfall and temperature, and on the activity of living organisms. The relief can also be a factor of considerable importance where areas of marked differences in elevation are compared under similar climatic conditions.

Physical forces

The most important initial agents of weathering of rocks are likely to be physical. If the rocks are at the earth's surface they undergo daily and seasonal changes in temperature which of course constantly produce expansion and contraction. The contrast is particularly great where the surface of the rock is exposed to sunlight while the remainder may remain cool. The difference in expansion of different portions of the rock is likely to cause cracking, flaking off or crumbling. The process of disintegration is accelerated if the rock is stratified, or if it consists of many kinds of minerals having different degrees of expansion.

Physical weathering is also brought about through freezing and thawing, much in the same manner as occurs through marked periodic changes in temperature at above-freezing levels. The water that penetrates any small or large cracks can quickly split off a rock segment when it freezes. Obviously then, the processes of heating at one time and freezing at another may work together to accelerate rock disintegration. Alternate wetting and drying produce similar results.

The process of soil formation is further accelerated in a broader way by the movement of water, ice and wind. The effect of water movement is much in evidence in rivers and small streams which carry or move large amounts of pebbles, sand and silt. The grinding action of these materials on themselves and on the stream bed may seem small when viewed in a single year, but over the centuries the Grand Canyon of the Colorado river was formed. When the sand and silt are deposited on a lower flood plain then we have a completely new soil which may sometimes be formed on another soil of entirely different origin.

Glaciers have also been major factors in soil formation, as, for example, in the soils of the Corn Belt. Soils and rocks that at one time were in southern Canada and the northern portion of the United States were scooped out, pulverized and mixed by the moving ice and deposited further south when the ice melted. The scouring and scooping action was responsible for the formation of the Great Lakes.

Wind may also move large amounts of soil in dry regions and deposit it elsewhere to form loess soils, or dunes consisting of piles of sand. Rock fragments so moved may exert a marked abrasive action on each other or where they strike undecomposed rocks. Like most other soil-forming processes, the action is slow but the total effect may be large when centuries are involved.

Chemical changes

Water, oxygen and carbon dioxide are the agents responsible for most of the chemical decomposition of rocks; other agents involved to a lesser extent are inorganic and organic acids. Seldom does any one of these agents work entirely alone. Pure water, for example, will dissolve most minerals at an extremely slow rate but carbon dioxide, released by microorganisms and higher plants, is usually present and carbonic acid is formed. This, or any other acid, dissolved in water, will greatly accelerate the removal of basic elements as it trickles over disintegrated rocks. Mineral elements, such as calcium and magnesium, may be dissolved out of parent material in one place but be deposited at a lower level in other locations. This is the way in which our limestones are formed.

Rock disintegration by hydrolysis is usually even more important than by simple solution. In this process, the water reacts with minerals to form new products that differ physically and chemically from the original parent material. The new products may be more soluble and be lost by leaching, or they may remain as colloidal materials and become a very important part of the new soil being formed. Clay is a product of this process. Oxygen of the air may also react with some minerals to form new substances that may be either more or less soluble than the original ones.

Biological activities

One of the most obvious and striking manifestations of biological activity is the splitting of rocks by tree roots that progress along fine cracks or stratification lines when small. Expansion of the roots as they grow may exert sufficient pressure to split the rock or at least cause small parts of it to be released.

The most important contributions of plants to soil formation, although less striking than rock splitting, are realized in their normal growth processes, followed by death and decay. During growth, they directly aid in the solution of rock minerals that they assimilate and, on death, leave at the surface. Root growth, itself, through both physical and chemical processes opens up the soil, improves the physical condition, and thereby favors infiltration of water. When the plants die, or as cells are sloughed off from the roots and root hairs, an appreciable quantity of organic matter is left, often at depths of several feet. Both the living roots and the residual dead organic matter favor the movement of water through the soil, and this is water that contains organic acids. This means more solution of minerals and sometimes more deposition of organic and inorganic materials at the lower depths. The net effect is that soil formation is hastened and extended to a greater depth, and soil fertility is increased. When plant residues, such as forest debris, decay at the surface with the formation of carbonic acid the leaching of bases from the soil profile is hastened. Some of the organic matter is also leached downward. This process is known as podzolization.

Animal life in and on the soil, which is of course dependent upon plant life, is also a considerable factor in soil formation, as is brought out in Chapter 4.

Microorganisms are likewise of major importance in soil formation, since they are primarily responsible for the decomposition of all forms of dead plant and animal life. Their chief residual product is soil humus, but in the process of forming it they release carbon dioxide and other organic acids that act directly on soil minerals. More information on the broad activities of bacteria, fungi and actinomycetes is given in Chapter 3 and in later chapters.

Climate, topography and time

In all of the processes of soil formation it is obvious that climate and topography, or relief, are major factors in determining the rate of formation of a soil and its final characteristics. If the rainfall is very limited, plant growth may be absent or scant. Likewise, microbial activity will be greatly curtailed since the growth of most microorganisms is directly related to total plant growth; it is the plant products that supply their needs for energy. Deficient rainfall also means limited water movement through the soil profile and hence greatly reduced solution or disintegration of parent materials. Desert soils, which are largely unleached, are usually basic in reaction; humid soils are commonly acid because of the constant removal of the bases by water containing acids. The distribution of the rainfall and the temperature range during the year are also important.

Soil formation is largely at a standstill in cold regions where the soil remains frozen for most of the time. If there is some freezing and thawing at the surface, there is of course some rock disintegration and mechanical mixing but the effects of plant and animal life, so important in warmer regions, are almost completely absent. The speed of chemical reactions increases 2–2.5 times for each 10° C increase in temperature. The same is true for the growth and activities of living organisms within their temperature range of growth.

Topography exerts its influence on soil genesis through its effect on run-off, drainage and erosion. A soil that is exposed at a high elevation tends to remain comparatively dry and has limited infiltration, whereas those at low levels may be moist, or in many cases actually submerged for long periods. Obviously drainage, aeration, water movement through the soil and the growth of higher plants and microorganisms are greatly different under the two conditions. Soils formed on rocky exposed areas have little depth, and for this and many other reasons support only limited plant growth. Well-drained, lower-lying soils in the same region are likely to have deep soil profiles, hold much more moisture, and are far more fertile and productive. Soil organic matter is likely to play a more important role in soil genesis under the latter conditions.

The transformation of igneous rocks into deep soils ordinarily requires many, many years under the most ideal conditions – at least a few centuries – and many soils are millions of years old. All of the factors mentioned above play their parts in determining the time required. Wind or water erosion may of course remove soil particles from the place of their formation to other regions and deposit them as loess or alluvial flood plain soils. In a sense, such soils are formed quickly, but actually this is not soil formation in the strict sense but merely soil transportation.

CHARACTERISTICS OF SOILS

The constituents of soils include residual mineral matter from rock weathering; living organisms including flora and fauna; organic matter or humus left as residual material after the death and partial decay of higher plants; air, usually with additional carbon dioxide; and water, both bound and free. Each of these components is not only highly important in soil genesis, as already pointed out, but also plays a major role in determining the suitability of the soil for crop production.

Mineral composition

The principal minerals of the igneous and sedimentary rocks of the earth's crust, according to Jeffries (1950), are quartz, feldspar, mica and clay minerals. In addition, other constituents designated as accessory minerals, iron oxides and carbonates, are also present. Table 2.I shows the estimated values as given by Jeffries.

The mineral composition of a soil is usually determined to a marked extent by the kinds and amounts of the minerals in the rocks from which the soil was formed, and by the nature and extent of the weathering processes. However, it should be emphasized that there are many exceptions to this statement. Often the physical and chemical changes are so great that the mineral content of the older soils shows little resemblance to that of the

TABLE 2.I

MINERAL COMPOSITION OF THE CRUST AND THE AVERAGE SEDIMENT OF THE EARTH (from JEFFRIES, 1950)

Mineral	*Crust (%)*	*Average sediment (%)*	*Average sediment, carbonate free (%)*
Feldspar	57.8	7.0	8.7
Quartz	12.8	38.0	47.5
Amphibole	16.0	–	–
Mica	3.6	20.0	25.0
Accessory	8.0	3.0	3.8
Clay	1.1	9.0	11.2
Carbonates	0.5	20.0	–
Limonite	0.2	3.0	3.8

parent materials. Often the original basic materials have been almost completely leached out, and chemical changes have completely transformed the residual mineral material. Laterite formation is a rather extreme example of this process. In this case the rock materials undergo slow and continued hydrolysis with the formation of silicic acid and aluminum and iron hydroxides. Such a soil has little organic matter or microbial life, and is very unproductive.

TABLE 2.II

THE APPROXIMATE COMPOSITION OF THE EARTH'S CRUST AND MEAN COMPOSITION OF THE A-HORIZON OF 18 REPRESENTATIVE SOILS (from BYERS et al., 1938)

Constituent	*Earth's crust (%)*	*Soils A-horizon (%)*
Aluminum oxide	15.34	9.97
Iron oxide	6.26	3.59
Calcium oxide	4.96	1.04
Magnesium oxide	3.90	0.60
Potassium oxide	3.06	1.73
Sodium oxide	3.44	0.82
Manganese oxide	0.10	0.14
Titanium oxide	0.78	0.90
Phosphorus oxide	0.29	0.14
Sulfur oxide	0.25	0.09
Silicon oxide	61.28	76.48

Almost any of the chemical elements may be found in soils, at least in traces, but actually most of the inorganic portion consists of a comparatively small number of these elements. This is because soils are formed chiefly from igneous rocks, shales and sandstones, 98% of which on the average consist of less than ten elements. In Table 2.II is shown the approximate composition, expressed as oxides of the elements, of the earth's crust and also the mean composition of the A-horizon of 18 representative soils. These data of Byers et al. (1938) emphasize the extent to which weathering removes the bases from the parent materials, leaving a higher percentage of the main constituent, silicon dioxide, in the residual material.

Texture

Soils are described on the basis of the percentages of the various particle sizes present without regard to their mineral content. In the order of decreasing particle sizes are the stones, gravels, sands, silts and clays with much of the clay being in the active colloidal form. The soil separates and diameters in mm, recognized in the United States, are: very coarse sand, 2.0–1.0; coarse sand, 1.0–0.5; medium sand, 0.5–0.25; fine sand, 0.25–0.10, very fine sand, 0.10–0.05; silt, 0.05–0.002; and clay, < 0.002 (*Soil Sci. Soc. Am. Proc.*, 1962, 26: 315). A soil always contains particles of various sizes and, depending on the dominant textural sizes, is designated as sandy clay loam, silt loam, silty clay loam, etc. A soil textural diagram, taken from the U.S. Department of Agriculture Soil Survey Manual (1951) is shown here as Fig.2.1. The proper class name of a soil is readily found by noting where two lines on the diagram intersect. One of these lines originates at the point corresponding to the percentage of silt in the soil and parallels the left side of the triangle; the other originates from the point corresponding to the percentage of clay and parallels the base of the triangle. This diagram emphasizes the importance attached to the clay and silt contents of a soil by soil scientists, and the comparatively minor importance of the sand and stones. Where coarse fragments are present in the soil material in

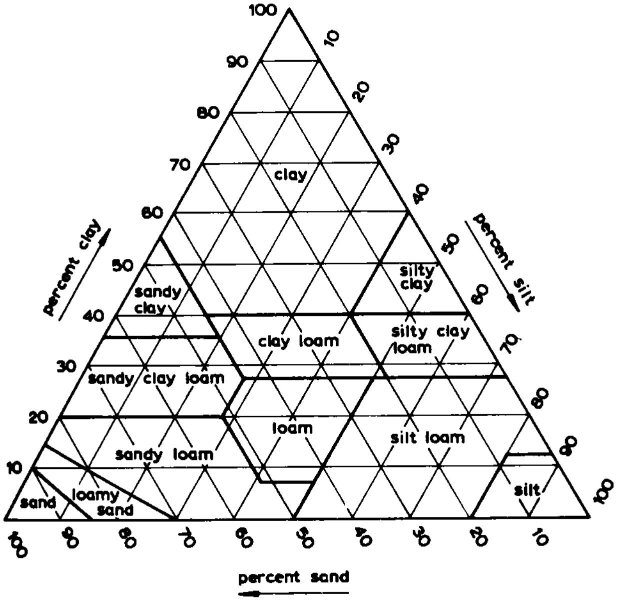

Fig.2.1. Chart showing the percentages of clay (below 0.002 mm), silt (0.002–0.05 mm), and sand (0.05–2.0 mm) in the basic soil textural classes. (From *Soil Survey Manual, U.S. Dep. Agric Handb., 1951*, 18. Prepared by Soil Survey Staff.)

appreciable percentages the textural soil class names are modified by the addition of suitable adjectives to the textural names shown in Fig.2.1.

Fertility and productivity of soils usually increase with decrease in particle size and increase in surface area, at least up to the point where other factors may become controlling. These other factors that are so likely to interfere with plant growth in the soils of finest texture are poor aeration, unsatisfactory aggregation, slow water infiltration and poor drainage.

It is the surface layer, called the A-horizon, that is of most importance in plant growth, and the descriptions or textural names mentioned above refer to this layer. The soil of the B- and C-horizons may be of markedly different texture and in such cases may sometimes play almost as big a role in plant growth as does the A-horizon. If the surface soil is very shallow, if hardpans form, or if the subsoil is high in nonaggregated clay particles, root growth can be markedly curtailed. This may be due directly to resistance to root penetration or to an unfavorable environment resulting from such factors as poor aeration, poor drainage, high acidity, or toxic compounds formed under reducing conditions. In regions of low rainfall there is less stratification of soil, or in other words, less well-defined profiles. The soil at a depth of six feet may differ little from that at the surface. It is in podzols, especially, that the profile is well-developed and the B-horizon is likely to differ markedly from the A-horizon in texture, structure and chemical characteristics.

Soil organic matter and microorganisms

The amount of organic matter in a mineral soil is an extremely important factor in the determination of its characteristics and suitability for use in agriculture. It is a substance that has many desirable properties and essentially no undesirable ones. It exerts its beneficial effects through physical, chemical and biological channels.

An abundance of organic matter favors a more rapid rate of water infiltration and consequently there is less run-off and erosion. The result is a greater supply of water for crop use, and better drainage. Humus tends to make very fine-textured soils behave like coarser-textured ones; the reverse is true for sandy soils.

Soils high in organic matter are recognized as fertile ones. This is chiefly because the organic matter is constantly releasing nutrients through base exchange reactions, through decomposition, and as chelated elements. Microorganisms, which are of major importance in determining the rate of release, are in turn dependent upon the organic matter for energy and nutrients.

Under ordinary conditions as found in the field, a small portion (perhaps 0.1–2.0%) of soil organic matter consists of living microflora in all stages of activity from the resting spore stage to active, rapidly multiplying cells. The transformation from the resting stage into the active vegetative stage can occur within a few hours when the moisture and temperature are optimum and when a supply of readily available food, such as crop residues, is added to the soil. In addition, the animal population in the soil is likely to be even greater in weight than the microflora but considerably less active per unit of mass. The sum total of the changes brought about by these two groups of organisms under optimum conditions can be far greater per unit of time than the physical and chemical changes that occur in the nonliving portion of the soil organic matter. The products of this biological activity include available nutrients, chelates, humic acids and miscellaneous compounds that are so important in determining humus properties and plant response. Often it is not realized that this living fraction of soil organic matter is of such great importance. The tendency in the past has been to emphasize the chemical nature of organic matter to a far greater extent than its biological aspects, even though it is the microorganisms that are largely responsible for the chemical nature of the rest of the material. Humus consists, in fact, largely of the residual products of biological action although most of them may have polymerized or reacted to form more complex materials. A considerable portion of the organic colloidal material that is considered so valuable is made up of living and dead microbial cells.

The major effects of organic matter, merely outlined here, are considered at length in later chapters.

Structure and porosity

The suitability of a medium- or fine-textured soil for use in agriculture is often just as dependent upon the arrangement of the individual particles in the soil mass as on the nature and composition of the particles. Normally clay and silt grains are held together rather tenaciously by physical and chemical forces to form aggregates. These aggregates may be of varying size but the water-stable ones are usually 1–2 mm or less in diameter. If larger than this, they tend to break down during cultivation or as a result of the growth of masses of finely-divided roots. But even in the absence of plants, constant wetting and drying, or freezing and thawing, will tend to break up the large aggregates. Fortunately, these same agencies can also at times help to form stable small aggregates where aggregation was initially poor. A high percentage of organic matter in the soil is a major factor in stabilizing aggregates.

A good soil structure is important because such a structure assures good water infiltration and ready movement through the soil column, good aeration, and good tilth. This favors root growth, ease of cultivation and a good environment for plant growth, particularly if the organic matter content is comparatively high. The well-known bad effects that result from plowing soils when they are too wet, thereby impairing their structure, emphasize how important a good soil structure is. Good tilth is a valuable soil property that must be maintained if crop yields are to be kept at a satisfactory level. This subject is considered in some detail in Chapter 16.

Surface area

One of the surprising and important characteristics of soils is their surface area. This

TABLE 2.III

SURFACE AREAS OF MATERIALS WITH NON-EXPANDING LATTICES (from GREENLAND and QUIRK, 1962)

Source	*Exchange cation*	*Fraction*	*CEC**1 *(me/g)*	*Surface area, m^2/g by adsorption of*		
				N_2	*CPB**2	H_2O
Illites:						
Fithian, Illinois	Na	< 2μ	0.26	93	96	–
Willallooka, S. Australia	Na	< 2μ	0.41	132	138	105
Kaolinites:						
Malone, Vic., Australia	–	As received	0.043	17	21	19
Rocky Gully, W. Australia	Na	< 2μ	0.050	36	36	29
Bath, S. Carolina	–	As received	0.028	18	15	15
Mesa Altra, New Mexico	–	As received	0.026	15	11	8
Lewistown, Montana	–	As received	0.014	14	11	13
Rotorua, New Zealand	Na	< 2μ	0.030	40	9	9
	Ca	< 2μ	0.030	41	9	12
Metahalloysites:						
Bedford, Indiana	–	As received	0.027	50	21	19
Djebel Debar, Ethiopia	–	As received	0.042	60	45	54
Oxides:						
Silica	–	< 200 mesh	0.052	155	67	115
Alumina (basic)	–	< 200 mesh	0.004	88	23	22
Alumina (neutral)	–	< 200 mesh	0	144	0	93
Allophane, New Zealand	Na	< 2μ (pH 4)	0	138	0	495
		< 2μ (pH 7.8)	0.50		43	

*1 Cation exchange capacity.
*2 Cetyl pyridinium bromide.

can vary over a range of 10- to 100-fold depending upon particle size, minerals present, exchange cation, presence of organic matter and method of determination.

Representative data for soil minerals are presented in Table 2.III and 2.IV, taken from the publication of Greenland and Quirk (1962). Montmorillonite has the highest surface area, ranging up to 800 m^2/g. This means that a 10-g sample has an area of approximately two acres or four-fifths of a hectare. This is certainly an impressive value. Kaolinites have surface areas ranging between 10 and 40 m^2/g, whereas illites have values intermediate between montmorillonite and kaolin. Cation exchange capacities tend to vary directly with surface areas. Of course the importance of the surface area depends upon the activity of the surface, particularly toward water.

We would like to have similar data for various kinds of organic matter but according to Greenland and Quirk this subject is still very much in the investigational stage. In fact, organic matter interferes very seriously with the determination of the surface area of soils and minerals. They state further that "there is evidence for covering and blocking of pores (by organic matter). In addition, organic matter tends to have external and internal

TABLE 2.IV

SURFACE AREAS OF CLAYS WITH EXPANDING LATTICES OR INCLUDING EXPANDING-LATTICE MATERIAL (from GREENLAND and QUIRK, 1962)

Source	*Exchange cation*	*Composition*[*1]	*Fraction*	*CEC*[*2] *(me/g)*	*Surface area, m^2/g by adsorption of*		
					N_2	*CPB*[*3]	H_2O
Montmorillonites:							
Upton, Wyoming	Na	–	$< 2\mu$	0.98	47	800	300
	Ca	–	$< 2\mu$	0.98	49	600	340
Redhill, Surrey	Na	–	$< 2\mu$	0.99	101	800	350
Interstratified illites:							
Grundy, Illinois	Na	–	$< 2\mu$	0.30	105	161	–
Sarospatak, Hungary	–	–	As received	0.16	43	152	57
Clays of mixed mineral composition predominantly Ca saturated:							
Macon kaolin	–	K, s, i	< 200 mesh	0.099	20	94	32
Chodau kaolin	–	K, i	< 200 mesh	0.080	25	50	30
Yooroobla clay	–	K, I, s	< 200 mesh	0.27	61	280	121
Colchester clay	–	K, I, s	< 200 mesh	0.18	77	194	82
Thulabin clay	–	I, s, k	< 200 mesh	0.19	70	98	72
Urrbrae loam, A-horizon	–	I, k	$< 2\mu$[*4]	0.15	61	165	144
Urrbrae loam, B-horizon	–	I, k	$< 2\mu$[*4]	0.33	153	255	132

[*1] K = kandites, I = illites, S = smectites. Capitals denote major components.

[*2] Cation exchange capacity.

[*3] Cetyl pyridinium bromide.

[*4] Samples as received but treated with 2% H_2O_2.

surfaces. For peat material, low-temperature nitrogen adsorption indicates a surface of 40 m^2/g but C.P.B. indicates that there may be as much as 300–500 m^2/g internal surface." We would certainly expect to find wide variations in the surface area of organic matter from different sources and having different degrees of humification.

Chemical properties

The most important chemical characteristics of a soil are: (1) its content of essential nutrients and their availability to plants; (2) the exchange capacity; (3) the buffering capacity; (4) acidity or alkalinity; and (5) content of inorganic and organic colloids (humus). Perhaps the state of oxidation or reduction of the soil should be mentioned; this is ordinarily not of major importance but may be if a waterlogged or poorly-drained soil is under consideration.

The specific importance of each of the six chemical characteristics of soils, mentioned above, need not be discussed in detail at this point.

THE SOIL PROFILE

When the farmer refers to his soil as a clay or sand, fertile or nonfertile, he is almost invariably thinking primarily of the plowed layer, and very incidentally of what is beneath it. This is not surprising because this is the part with which he deals constantly. But soils have depth – a soil profile – and the nature of the layers (horizons) not touched by the moldboard plow are often almost as important as the surface layer. It is in these deeper layers that a considerable portion of the plant roots must ramify if the plants are to develop properly. The nature of these subsoil materials also plays a major role in water retention and movement. They also serve to some extent as a source of plant nutrients. The terms A-, B-, C-, and D-horizons are commonly used to designate the surface soil, subsoil, partly weathered rock material, and unweathered rock material, respectively. These horizons may, or may not, be sharply defined. They may also be further subdivided. Under coniferous vegetation, as is pointed out later, the differentiation of horizons is usually very sharp, whereas in areas of limited rainfall there is usually only a gradual transition from one horizon to another. It is the quantity and movement of water through the soil layers that is chiefly responsible for the development of the profile. But the nature of the profile is also markedly affected by the kind of vegetative cover on the soil which, in turn, is determined chiefly by the climate. All of these factors, and of course the nature of the parent rock material, exert major effects. This is seen by comparing the soil profile taken from a forested area with one taken from a grassland or a semi-arid region. The former has sharply-defined A-, B-, and C-horizons, often with layers of hardpan; the latter may show little change in the nature of the horizons to a depth of 5 or more ft. Where rainfall is inadequate for downward movement to the water table (if there is one) the conditions for marked stratification do not exist.

Soil profile development is a very slow process starting from the parent rock. Rock disintegration at the surface can proceed at comparatively rapid rates because water, oxygen, and microorganisms are commonly present in abundance, and sudden marked changes in climatic factors are common. Below the upper few inches the change from rocks to soil is an exceedingly slow process and proceeds at only a small fraction of the rate at the surface. All soil formation occurs in indistinct steps and stages throughout the profile with considerable overlapping of profiles. As weathering and biological activities proceed there is an accumulation of soil materials that are either undecomposed or changed to water-insoluble compounds. Clay minerals are also formed and as this process proceeds there emerges a medium that is markedly different in chemical and physical properties from the starting materials. As soon as such a medium can support plant growth the transformation into soil proceeds more rapidly in the A-horizon and is more in evidence as a result of the accumulation of plant residues. Changes also occur in the B- and C-horizons but the nature of these changes vary with each soil. It is the variations in the changes that help to differentiate horizons in the soil profile.

The process of soil horizon formation involves both gains and losses of constituents as well as slow continuous alterations in the composition of the soil mass. The kinds and rates of these changes vary in different parts of the profile and this in large part accounts for the formation of different kinds of profiles and for differences in any part of a single profile. These changes include the accumulation of organic matter in the upper layer and the movement of clay and sesquioxides to lower depths. As minerals in the parent material are dissolved they move downward with the water and are either precipitated at lower depths or pass into the ground water. The deposition of these minerals, particularly iron oxides, along with organic matter may help materially in outlining some of the horizons of the profile. In drier regions, where the rainfall is inadequate for much if any leaching, soluble salts may accumulate in the profile to such an extent as to form an alkali soil.

The organic matter content of the soil horizons formed under different conditions of climate and vegetation vary markedly. This organic matter tends to stratify in humid regions, whereas in drier regions it remains largely where the plant parts are formed and where they decay. In the humid region the organic matter plays an active and major role in the development and appearance of the soil profile, but in nonhumid regions it is largely inactive except in the sense that it serves as a source of food for microflora and microfauna.

Profiles that are encountered initially in agriculture, especially in the United States where many soils have been under cultivation for less than 100 years, are the profiles that developed under virgin conditions – either forests, grasslands, or desert shrubs. When the native plant cover has been removed, and cultivated crops have been grown for many years, the original profile is changed, and sometimes very markedly in the A- and B-horizons. This change is the result chiefly of a change in the vegetative cover, since the climate remains essentially the same. Heavy fertilization including liming, better drainage, elimination of hardpans, and the introduction of other good farm management practices, often exert major effects. Marked modification of the natural soil profile can sometimes occur in a fraction of the time required for the development of the original soil profile. A podzol, formed under a forest type of vegetation, which has a very distinctive well-developed profile, may be changed under intensive mixed farming to such an extent that it can scarcely be recognized; grassland soil profiles would be very much less affected.

SOIL CLASSIFICATION

The above brief discussion of soil formation and characteristics emphasizes the wide variations that can and do exist in nature, even in comparatively small areas. In order to understand better a given soil and to know its value and relationship to other soils in other regions much effort has been put forth in an endeavor to classify soils. Our knowledge of soils and their formation has increased markedly during the past 75 years and with increases in basic knowledge have come constant and frequent changes in our schemes of classification. An extensive discussion of this subject falls outside the realm of this book. Suffice it to say that an excellent outline of the main facts, principles involved, and bases of soil classification is given by Baldwin et al. (1938). A more recent and comprehensive system of classification has been presented by Smith et al. (1960) but there is still no world-wide agreement as to how soils should be classified.

Our knowledge of soils in a given area and how they can be utilized to best advantage is greatly aided by the construction of soil maps. These show the location and size of the area of each particular soil group. Ableiter (1938) tells how these soil maps are made and utilized in soil management. A map of the soil associations of the United States, as drawn up by the U.S. Dep. of Agriculture, is also shown in the *Yearbook of Agriculture* for 1938. Much information for each of the soil associations is given on geographic setting, climate, native vegetation, parent materials, soils and their use.

REFERENCES

Ableiter, J.K., 1938. In: *Soils and Men – The Yearbook of Agriculture, 1938.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C.,pp. 1002–1015.

Baldwin, M., Kellogg, C.E. and Thorp, J., 1938. In: *Soils and Men – The Yearbook of Agriculture, 1938.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., pp. 979–1001.

Byers, H.G., Anderson, M.S. and Bradfield, R., 1938. In: *Soils and Men – The Yearbook of Agriculture, 1938.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., pp. 911–928.

Greenland, D.J. and Quirk, J.P., 1962. *Trans. Jt. Meet. Comm. IV and V, Int. Soil Sci. Soc., N.Z.* Wright and Carman, Wellington, pp. 79–87.

Jacks, G.V., 1954. *Soil.* Nelson, London, 221 pp.

Jeffries, C.D., 1950. In: D.E.H. Frear (Editor), *Agricultural Chemistry.* Van Nostrand, New York, N.Y., 1: 745–762.

Simonson, R.W., 1957. In: A.S. Stefferud (Editor), *Soil – The Yearbook of Agriculture, 1957.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., pp. 17–31.

Smith, G.D. and Soil Survey Staff., 1960. *Soil Classification – A Comprehensive System, 7th Approximation.* Soil Conservation Service, U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., 265 pp.

Chapter 3

MICROFLORA OF SOILS

INTRODUCTION

The microflora of a soil is an intimate part of soil organic matter; in fact, much of the colloidal portion of humus consists of living and dead microbial cells or their disintegrating residues. The remaining portion, consisting of residual decomposition products of plant and animal tissues, owes its properties primarily to the activities of the microflora. The quantity and characteristics of organic matter in any given soil are therefore so dependent on the nature of the microflora and their biochemical transformations that no discussion of the role of soil organic matter in plant growth would be complete without a consideration of this microflora population. The lesser part played by the micro- and mesofauna in soil organic matter formation and decomposition is considered in the following chapter.

Four groups of organisms, other than viruses, constitute the microflora population of soil. These are bacteria, actinomycetes, fungi and algae. Each of these groups is made up of many genera and hundreds of species. A listing of the bacterial genera alone, commonly found in soils, would probably include half of those listed in Bergey's *Manual of Determinative Bacteriology* (Breed et al., 1957). New species are still being described from time to time. In the present book it is sufficient to discuss in a general way the types of microorganisms found in soil and to list their main contributions to soil fertility and plant growth. Taxonomy will not be dealt with except in an incidental way.

BACTERIA

Numbers and mass

Bacteria constitute the most numerous group of microorganisms in soil, and they are also the smallest living organisms, apart from viruses that live in the cells of other organisms. Bacteria may be of various shapes, including round, rod-shaped, spiral and filamentous. In size they commonly range between 0.5 and 5.0 microns in diameter but most of them are within the one to two micron range. The number of bacteria per gram of soil varies greatly and the population curve can go up or down very strikingly within a period of a few days or even hours. Most uncropped soils of average fertility that have received no recent additions of organic matter are likely to contain 10–100 million of bacteria per g as determined by plate counts. Where abundant supplies of organic matter have been added recently it is not unusual to find as many as one or more billions of active bacteria per g. Where counts are made by direct microscopic examination rather than by plate cultural methods the number may be at least 5-fold higher. It is generally assumed that such direct counts include a high proportion of dead bacteria, but direct quantitative data on this are not available.

Estimates of the weight of bacteria in soil vary from about 300 to 6,400 lb. per acre 6 inches, with the higher values applying to soils cropped to legumes. Clark (1967) states that with a bacterial count of 2 billion cells per g of soil the live weight of bacteria would be about 4,000 lb., or 0.2% of the soil weight. He further estimates that for a soil containing 0.3 ml water per g a bacterial population of 2 billions will occupy only about 1.3 % of this water volume.

Field soils have been shown experimentally to give off about 0.8–2.2 lb. of CO_2 per acre per hour. Clark (1967) points out that the bacteria represent only about one-fifth of the biomass in the soil. The production of about 0.3–0.4 lb. of CO_2 by the bacteria alone is so much below what would be expected from a 2 billion per g bacterial count that Clark considers this to be strong evidence that there are not that many active vegetative cells present. The CO_2 figures are more in line with counts of 50 million per g commonly reported for field soils by plate counts. This would seem to indicate that direct plate counts give a better idea of active bacterial numbers and activity than do the much higher direct counts. If the numbers are actually as high as 2 billions, the logical conclusion is that most of them are either very inactive or dead.

Types of bacteria based on energy source

Bacteria are of two general types. These are heterotrophic that depend on organic compounds, synthesized by chlorophyll-containing plants, for their nutrition; and autotrophic that are either able to oxidize certain inorganic compounds or which contain chlorophyll and can utilize sunlight as their energy source. The photosynthetic bacteria are not an important factor in soil and hence need not be considered in the present discussion.

Heterotrophic bacteria

The large majority of soil bacterial species, and nearly all of the mass of bacteria in normal soil, consists of heterotrophic organisms. The "biological explosion" that follows the addition of readily available energy sources to soil is produced by these bacteria together with actinomycetes and fungi, discussed later. Many of these bacteria have generation times at room temperature of 20–60 min.,and it is this rapidity of division that accounts for the extremely rapid increase in numbers and CO_2 production under ideal conditions for growth.

Essentially every naturally-occurring organic compound that is formed in, or gains entrance to, the soil is subject to attack by one or more, and usually many, species of bacteria. These include very readily decomposable sugars, starches, fats and proteins; less readily-attacked celluloses and hemicelluloses; and still more resistant lignin, waxes and various aromatic substances. The bacteria utilize these carbon-containing materials primarily as sources of energy but may also obtain mineral nutrients, growth factors, and miscellaneous substances that they require for their growth processes. They utilize available energy sources at a rapid rate, and apparently in a wasteful manner. Most of the readily available food sources are used quickly and then most of the bacteria die off, leaving a small percentage in a resting condition, either as spores, or in other resistant forms.

The heterotrophs vary greatly in their morphology, physiology, growth requirements and in the biochemical changes that they bring about. Most of these bacteria require oxygen for growth, others are obligate anaerobes, whereas many are facultative. Some form spores but many do not. Some can synthesize all of the growth factors that they need but others require outside sources of certain amino acids, biotin, nicotinic acid, etc. A few can utilize atmospheric nitrogen but most of them must obtain their nitrogen from the soil or from the material that supplies their growth energy.

Many of the heterotrophs grow well at room temperature whereas others grow only in the thermophilic range of 50–70°C. Some species are adaptable to a range of temperatures, usually preferring the mesophilic range of 25–35°C but tolerant of temperatures of 50°C and above. In general, the products of decomposition produced by the thermophiles are similar to those produced by the mesophiles, but at the higher temperatures the rate of decay is greatly accelerated.

The optimum pH for the growth of most bacteria is near neutrality. The range of pH at which good growth occurs is usually between 4 and 10, with the growth diminishing sharply as the extreme parameters are approached. A few bacteria can live at pH values of less than 4 but growth at this acidity is usually sparse. Sensitivity of bacteria to acidity is a very important characteristic that often largely controls the overall composition of the biomass in soils. Many soils in the humid region are too acid to permit a vigorous growth of bacteria. Under such conditions the fungi commonly become dominant. However, when large amounts of plant materials are added to very acid soils, bacterial multiplication can often proceed at a rapid rate for a time because under these conditions the organisms are largely insulated from the acid soil mass.

Nitrogen-fixing bacteria are present in most cultivated soils but not in large numbers. These include the nonsymbiotic or free-living bacteria, and the symbiotic forms that live in nodules on the roots of leguminous plants. Both types of bacteria live in the soil or organic substances, but the symbiotic forms, after entering the plant root, obtain their energy from the juices of the higher plants. All symbiotic bacteria are aerobic and mesophilic; some genera of nonsymbiotic nitrogen-fixing bacteria are aerobic and some are anaerobic, but all are mesophilic. All of these bacteria can utilize either the common forms of fixed nitrogen or can obtain all of their nitrogen from the air (see Chapter 10).

The denitrifying bacteria deserve special mention because of their practical importance. They are chiefly mesophilic heterotrophs that commonly grow aerobically on various carbon sources but can also grow anaerobically if supplied with nitrate that serves as a hydrogen acceptor in place of oxygen. In the process of utilization of the nitrate they reduce it to nitrite and then to free nitrogen gas. Under pure culture conditions in the laboratory such destruction of nitrate can occur within minutes if the oxygen is completely absent. Under field conditions the process is slow, because the population of vegetative cells is commonly small, and the soil is usually not completely free of oxygen even under conditions of excess water unless permanently submerged. An abundance of readily available carbon sources favors denitrification greatly, since the bacterial population is increased following their addition, and oxygen utilization and carbon dioxide evolution are favored (see Chapter 13).

The principal factor that limits bacterial growth in soil is the energy supply, which means organic substances, since most soil bacteria are heterotrophic. Besides this, other factors that affect bacterial activity are the physical ones – moisture, aeration, and temperature – and soil reaction, already discussed. Most of the nutrients required by higher plants are also required in at least trace amounts by bacteria. Of these, nitrogen and phosphorus are the most important, but the mineral nutrients are needed in such small amounts that most organic substrates on which they grow furnish all that are needed. It is the energy food supply that is of paramount importance.

Biotic effects also play a major role in bacterial growth. Competition is extremely keen in the soil both among the various species of heterotrophic bacteria and also between the bacteria, actinomycetes and fungi. The most rapidly growing organisms, and the ones that can attack a variety of food sources, are most likely to become dominant. But there is also the matter of antibiotic production that often enables one organism to prevent another from growing (see Chapter 18). Frequently the faster-growing organisms utilize the readily available energy sources and then die out leaving other bacterial species, or perhaps actinomycetes and fungi, to attack the more resistant substrates. It is the food specialization that often makes possible the co-existence of many kinds of organisms in the soil. Conditions change with time, allowing one species to be replaced by another. Even antibiotic-producing organisms do not have the advantage over others for any great length of time. Antibiotic production continues only so long as its producer can grow, and then the antibiotic is subject both to adsorption by clays and to biological attack by other species.

Autotrophic bacteria

Autotrophic bacteria are those that have the ability to obtain their needed energy supply by oxidizing inorganic compounds, and can use carbon dioxide as their sole source of carbon. Organic compounds are not utilized by strict autotrophs and in some cases are believed to be inhibitory to growth. So far as growth in soils is concerned, any such inhibition has probably been much overemphasized. Most autotrophs seem to grow best in soils that are well supplied with humus; it serves as a source of carbon dioxide, mineral nutrients, and acts as a buffer against acids and alkalies. In extreme cases, as in heavy animal manuring or where a green manure crop is turned under, it is conceivable that the organic decomposition products are soon eliminated by the heterotrophs, leaving conditions ideal for the autotrophs. Quantitative evidence for this viewpoint is scarce, but qualitative observations are abundant. For example, if one is seeking a soil of high nitrifying capacity for use as an inoculant or in nitrification experiments, he invariably selects a garden soil that has received much organic matter year after year. Similarly, the writer observed repeatedly that a Harpster clay loam from Iowa that contained about 7.5% organic matter had a nitrifying capacity that exceeded all other soils tested, with the possible exception of an occasional garden soil.

Since autotrophic bacteria comprise a very small portion of the biomass in soils and are not involved in organic matter decomposition, an extensive discussion of them is unnecessary. When they die they do of course contribute to the soil organic matter supply, synthesized from carbon dioxide, but the amount is infinitesimal.

Our knowledge of autotrophic bacteria is still limited and very incomplete. The genera most studied and of most interest in the present discussion are *Nitrosomonas* that oxidizes ammonia to nitrite; and *Nitrobacter* that converts the nitrite to nitrate (see Chapter 12). These organisms that play a very important role in the transformation of nitrogen are obligate aerobes and are found in nearly all soils, but not in large numbers.

Other autotrophic organisms include *Thiobacillus* that oxidizes sulfur or sulfur compounds to sulfate; *Ferrobacillus* that converts ferrous iron to ferric; and several genera, not well understood, that can oxidize carbon monoxide, hydrogen and possibly other elements or compounds. Some of these bacteria, other than the nitrifiers, *Thiobacillus*, and *Ferrobacillus*, are known to be facultative autotrophs. Such organisms may utilize either inorganic materials or organic substances as energy sources. *Thiobacillus thioxidans*, studied by Starkey (1925), is unique in that it is able to grow at reactions near pH 0. This high acidity is produced by the organism as it oxidizes sulfur autotrophically to sulfuric acid.

ACTINOMYCETES

The actinomycetes constitute a group of organisms that morphologically and physiologically fall between the true bacteria and the fungi. At one time they were considered as fungi and were called "ray fungi", but they are now classed as more like bacteria than fungi. They are a very variable group of organisms morphologically, physiologically and culturally. Genetic changes, including mutations, have been observed comparatively frequently.

Actinomycetes occur in soils in numbers ranging up to a high of about 200 millions per g, which makes them second only to the true bacteria. In manure piles and similar environments the numbers may be 10 to 20 times this value. They have a unicellular mycelium with long branching hyphae that may develop in the soil or on the surface. The aerial mycelium, which is usually 0.5–1.2 μ in diameter, commonly breaks up into fragments that resemble bacteria. Some of the hyphae are branched and bear many asexual spores, called conidia. The masses of these resting conidia undoubtedly account for most of the high numbers of actinomycetes counts although the fragments of mycelia can also form colonies on agar media. The simultaneous presence of vegetative and resting cells makes meaningful counts difficult to make, or at least to evaluate in terms of activity of the organisms under a given set of conditions. This situation is comparable to that encountered in the enumeration of fungi.

A colony of actinomycetes on agar may consist of both vegetative and aerial mycelia. If aerial mycelium is formed, the surface has a powdery or cottony appearance; if absent, the colony is likely to be glossy. The colonies vary markedly in size, shape and color depending on the medium and cultural conditions. They often resemble those of fungi except that they are far less spreading and more pellet-like. Since multiplication is not by simple binary fission, as in the true bacteria, growth is usually much slower and not exponential. It is this slow growth on agar plates that accounts for their being largely ignored in the early years of microbiology. It is now realized, however, that they can at times be the dominant microflora in soils, manure piles, and wherever plant residues are undergoing decomposition. Among the products of their activities are soil humus or humus-like materials.

Actinomycetes are mostly aerobic, thus resembling the fungi. They grow best in neutral or alkaline soils and most of them have a pH growth limit of near 5.0, which is somewhat higher than for most soil bacteria. One of their outstanding characteristics is the ability to grow abundantly on decaying vegetable matter, such as straw or grass, at moisture levels so low that both true bacteria and fungi cannot compete vigorously. Under such conditions the vegetable matter may become matted with the mycelia. A characteristic musty earthy odor, commonly noted, is definite evidence for the presence of a dominant flora of the organisms. According to Küster (1967) the major aroma-producing substances are acetic acid, acetaldehyde, ethanol, isobutanol, isobutylacetate and possibly hydrogen sulfide. The aerial mycelium is often chalky-appearing or variously pigmented and this serves as further evidence of the presence of the actinomycetes in abundance. These organisms can grow well at higher moisture levels if aeration is not curtailed, but under such conditions these slow-growing organisms cannot compete on an equal basis with the fast-growing bacteria and fungi.

Both mesophilic and thermophilic species are found. The former thrive at about the same optimum temperature range as true bacteria but do not grow as well at the lower temperatures; the thermophilic species grow best at about 50 to 65°C but some of these are facultative thermophiles and can also grow at room temperatures. The fact that many actinomycetes thrive at comparatively high temperatures and low moisture contents adequately explains their abundance in fermenting strawy manure heaps, moist hay and other vegetable materials. In the decomposition of such materials the common observation is that fast-growing bacteria and fungi are responsible for the initial stages of the degradation involving the readily available carbohydrates and proteins. Then the actinomycetes begin to gain dominance since they can utilize resistant materials more readily than can the fast growers and can better tolerate moisture deficiency. The nitrogen supply is always a major factor in the biological succession; bacteria thrive on proteinaceous substrates, whereas both fungi and actinomycetes can make a surprisingly large amount of growth on a minimum amount of nitrogen.

The ability to produce antibiotics is common among the actinomycetes and much of the interest in these filamentous bacteria in recent years may be attributed to this fact. This interest has been manifest chiefly in research connected directly or indirectly with medicine. Soil samples from all over the world have been examined in the search for new species and strains that may produce a new antibiotic suitable for medical use. Hundreds of these antibiotics have been isolated but only a few have been found to be sufficiently non-toxic and specific for use in disease control. Among the best known of these that are in use are streptomycin, terramycin, aureomycin, cycloheximide, chlortetracycline, oxytetracycline, chloramphenicol and neomycin. Some of these have been used to a limited extent in disease control in plants. Their use for this purpose is limited by cost, by difficulty in getting the antibiotic into the plant, and by toxicity when used at concentrations adequate to be effective. The limited time that they are effective is also an important factor (Brian, 1957; Zaumeyer, 1958; Pramer, 1959). The role of antibiotics in soils and their effect on microbial ecology is considered in Chapter 18.

Actinomycetes play a very important role in humus formation largely because of their ability to attack such a variety of comparatively resistant substances. Among these substances are cellulose and other polysaccharides, hemicellulose, keratin, chitin and oxalic acid. According to Küster (1967), little is known about their ability to decompose lignin. The various high-molecular weight plant substances are converted into humic acids under a wide variety of conditions with respect to the physical environment. The first steps in this process are brought about by actinomycetes and other microorganisms and then the initial breakdown products are transformed chemically into highly polymerized humic acids. It has been observed by various workers that when *Streptomyces* undergo autolysis many of the species form dark brown substances that have chemical and physical properties closely resembling soil humic acids. These organisms serve as excellent material for the study of the formation and nature of humic acids. They are believed to be very important in humic acid formation in nature, and are commonly very abundant under conditions where humus is being formed. Although humic acids are considered very stable, Küster states that "some microorganisms, mainly *Nocardia* spp., are capable of decomposing humic acids, probably because of their ability to utilize heterocyclic N-compounds."

FUNGI

Fungi usually constitute the third most numerous group of microflora in the average cultivated soil, but the fungal mass is likely to be greater than the mass of either the true bacteria or the actinomycetes. The importance of these three groups of microorganisms in terms of organic matter decomposition and other biochemical changes is roughly proportional to their relative masses and not to numbers. The fungi do not of course always rank first in biological activity, because each group of organisms is affected differently by such factors as type and amount of organic material present, pH, moisture, temperature, aeration and all of the other environmental factors.

The fungal population of soils constitutes a very heterogenous group of organisms. The same can be said of bacteria and actinomycetes but possibly not to the same extent as for the fungi. As Warcup (1967) states, the fungi known to occur in soil cover the range from chytrids to agarics, from saprophytes to root parasites, and from parasites of amoebae to parasites of man. Attention will be given here primarily to those that play a role in soil organic matter formation and transformation and in other respects act as the true soil fungal flora. Little consideration need be given to plant-infecting fungi other than the mycorrhiza that are truly soil organisms and presumably beneficial aids in plant nutrition.

The determination of the number of fungi present in a soil is difficult, as in the case of actinomycetes and for the same reason. Fungi exist in soil in the form of masses of branching filaments which may or may not be separated into cells. These filaments are commonly about 5 μ in diameter but the size varies with the species, and the length is indefinite. In addition, masses of sexual and asexual spores (conidia) are formed which may remain in a dormant condition for months or years. If counts are made by the usual agar plate method it is generally agreed that most of the colonies observed are derived from these inactive spores. However, if the soil is vigorously agitated before plating, the vegetative filaments may be broken up into a variable and unknown number of fragments each of which may be able to produce a colony. The numbers determined therefore may have little meaning in terms of biological activity, but tend more to show which species sporulate most abundantly.

All fungi are heterotrophs, that is, dependent upon organic substances for their energy supply. They are also predominantly aerobic, and hence are usually found at or near the surface of any organic matter upon which they may be growing. In soils they are limited largely to the plow layer, or A-horizon, but this is because an abundant supply of energy sources is available only in this upper region.

The statement has often been made that fungi prefer an acid environment. This is not true. Instead, nearly all fungi grow best at pH 7 or above but they are far more tolerant of acidity than are other microflora. It is not unusual to observe fungi growing at pH 2.0, or even lower. This acid tolerance, plus their ability to grow rapidly, accounts adequately for their major importance in soils. In very acid mineral soils they have little competition from other organisms and they are commonly dominant if there is an appreciable amount of organic matter present.

Fungi are not only tolerant of acidity but many of them are tolerant of comparatively high concentrations of salts and also of unfavorable environmental factors. Starkey and Waksman (1943) isolated two cultures of fungi, *Acontium velatum* and a green organism belonging to the Dematiaceae, that grew at acidities of near pH 0. They also grew nearly as well at these pH values when the medium was saturated with copper sulfate. These two fungi, together with the species of *Thiobacillus*, previously mentioned, can tolerate the highest acidities of any living organisms so far described.

The majority of the fungal species are mesophilic, but a few can tolerate temperatures in the lower thermophilic range. In moisture requirements they differ little from bacteria. Any tendency toward waterlogging of a soil is very detrimental but primarily because of reduced oxygen supply and not because of excess water itself.

Fungi have low nitrogen demands in contrast to most bacteria. Their nitrogen needs are commonly obtained from the substances that they are decomposing, but inorganic nitrogen sources are also readily utilized. The writer has frequently observed vigorous growths of fungi on sawdusts made from woods that contained only 0.1% nitrogen. Under such conditions the rate of carbon dioxide evolution is increased, at least initially, by additions of ammonium salts or nitrates, but the increase is usually far less than might be expected. These microorganisms grow best when the nitrogen supply is fairly abundant but they are adaptable to low levels in much the same way that they are to low pH values. Many of the fungi readily attack cellulose and a few of them can utilize lignin. This makes them rather aggressive competitors with bacteria and actinomycetes for the plant materials that gain entrance to soils.

The efficiency with which energy sources are utilized by fungi is high when expressed in terms of carbon assimilated. During the first few days of growth on a sugar medium in the laboratory it is common for fungi to convert 40–60% of the carbon into cell material and the remaining part into carbon dioxide. In contrast, most bacteria will use only 20% or less of the sugar carbon in building cell material and convert the remainder into carbon dioxide. Azotobacter, for example, with its unusually high rate of respiration is likely to release 90% of the sugar carbon as carbon dioxide. This high efficiency on the part of the fungi must play a considerable role in soil organic matter formation and maintenance in soils. Some of these fungi are known to synthesize lignin or lignin-like materials, carbohydrates, and nitrogenous materials that are not greatly different from those found in humus.

Pinck and Allison (1944) grew cultures of filamentous fungi on a mineral-sucrose medium and found that the average contents of lignin or lignin-like substances in the mycelia of the various genera were *Cladosporium* 21, *Helminthosporium* 19, *Humicola* 8, *Dematium* 7, *Alternaria* 7, *Aspergillus* 6, *Metarrhizium* 4, and *Gliocaldium* 2. The black or brown fungi contained the highest percentages of lignin complexes and the light-colored organisms the lowest percentages. Under the best experimental condition *Cladosporium* and *Helminthosporium* converted 40–50% of the sucrose carbon into cell material. The carbon–nitrogen ratios of the fungal materials of the several genera ranged between 11 and 22% with an average value of 15%. Since the high lignin-synthesizing organisms grow mostly on decaying vegetation at or on the soil surface, they would undoubtedly be favored by a system of trash-mulch farming, or one of minimum plowing.

An interesting type of fungal growth, known as fairy rings, is often observed in grasslands, lawns, forests and other undisturbed places (Shantz and Piemeisel, 1917). Typically on lawns or pastures, one will see a circle or half circle pattern on the grass consisting of an inner zone where the grass is stimulated, a middle zone of dead or injured grass, and an outer zone where the grass is also stimulated and very green. Each of these zones is likely to have a width of perhaps six inches. These fairy rings are caused by the growth of soil-inhabiting fleshy fungi, mostly *Basidiomycetes*, and since several species are involved the nature of the rings varies considerably. At times when weather conditions are favorable the fruiting bodies (mushrooms) form in the bare zone, or at the junction of this zone with the outer zone, thus visibly and strikingly outlining the exact position of the fairy rings.

The fairy rings continue to spread outward from year to year at the rate of one or two inches to perhaps a foot a year. There is at least one claim of a spread of up to one meter per year. Shantz and Piemeisel give an average value for the yearly outward growth of 12 cm with a range of 0–60 cm. The width across the rings varies from a few meters to 70 m. The first year the fungal filaments grow outward in all directions, forming a circle of a few inches in diameter with perhaps little evidence of rings. After a few years the rings may sometimes be complete and circular, but more often they are broken at certain points, and the larger rings are usually formed by a series of arcs which do not come into contact with each other. When fungus filaments approach each other, they turn aside and ring formation is stopped. Exact data on the age of the rings is not available but estimates of 50 to 100 years, or longer, have been made.

The explanation for fairy rings is simple. The fungus feeds on the soil organic matter and gradually spreads outward into new areas as it exhausts the food supply. In the process of utilizing the organic matter as an energy source the nitrogenous materials are broken down into ammonia which is soon nitrified. This available nitrogen supply accounts for most of the new growth of grass. The grass in the middle of the ring is killed, according to most authors, as a result of drought. The fungus mat repels the entrance of water from rains or by capillarity (De Bano, 1969). Savage et al. (1969), for example, found that the iron and aluminum salts of a humic acid extracted from another fungus, *Stachybotrya atra*, rendered sand and soil practically impermeable to water. Most of the work on fairy rings was done prior to the age of antibiotics and we can only guess as to whether these substances play a role in the whole phenomenon. Even though the various fungi are dependent on soil organic matter for their food supply it has been observed repeatedly that they seem to grow best on soils that are relatively low in organic matter. This may be due more to the depressing effect of high available nitrogen on fairy ring production than to the harmful effect of organic matter per se.

Certain fungi have the ability to establish a relationship with many higher plants that seems to be mutually beneficial in most instances. These organisms are known as mycorrhizal fungi. This relationship is somewhat comparable in final results to the symbiotic association between *Rhizobium* and leguminous plants although the mechanics of the association, and the benefits realized are very different. In the case of fungi there are two kinds of mycorrhiza, endotrophic and ectotrophic. The former penetrate into and continue to live in the plant root cells, whereas the latter form a mat around the roots with minimum cell penetration. Many types of plants, especially trees and shrubs, but also cultivated plants, have these mycorrhizal associations. In some cases the higher plants seem to require these organisms for normal growth, at least under some conditions, and likewise the fungi are not able to grow except on their host, and the host is often specific.

The mycelia of the ectotrophic mycorrhiza often largely replace the root hairs and seem to act as their substitute in nutrient uptake. Our knowledge of how mycorrhiza function is inadequate, and the exact mechanisms by which the fungi benefit their host are largely unknown (see Chapter 5 and 28).

ALGAE

Algae are found in nearly all cultivated soils in numbers that vary from a few hundred to several millions per g. As in the case of fungi and actinomycetes, numbers have little meaning since algae vary so greatly in morphology and rate of growth. Many species are unicellular, commonly 2–5 μ or even more in diameter. Other species are filamentous, 2–5 μ in diameter and 10–50 times as long as they are wide. In fact, the writer has repeatedly observed cultures of *Anabaena* and *Nostoc* in which the filaments were so long that the mass of growth as observed under the low power of a microscope seemed to be endless. Such long filaments are commonly septate, that is, divided into many cells that are not much longer than wide. Colonies that develop on agar may be derived from unicellular algae, from one or more cells of a broken filament, or from a gelatinous mass of filamentous algae consisting of thousands or even millions of cells. In addition, spore formation is common among algae and these inactive cells also form colonies readily when conditions are favorable.

Soil algae comprise the grass-green Chlorophyceae, the blue-green Cyanophyceae, and the diatoms or Bacillariophyceae. All algae are autotrophic, chlorophyll-containing organisms, although some species can live in the dark and use simple carbohydrates as their energy source. In nature, however, their heterotrophic physiological and biochemical activities are probably so limited that for practical purposes they can almost be considered as nonexistent. Active growth of algae in soils is limited almost entirely to the upper few millimeters where light is adequate. Algae are usually considered as being primarily aquatic organisms. The soil forms are somewhat smaller than the water forms and apparently have become adapted in the course of time to soil which is a rather unfavorable environment for growth most of the time.

The grass-green algae are the ones that are most in evidence in soils. This is because they can tolerate soil acidity and have a fairly rapid rate of multiplication. In the spring and fall months during rainy periods these organisms can frequently be observed in the low-lying areas, in soil depressions, or in moist partly shaded areas, as a light to heavy green surface covering on soils that are otherwise bare. Or they may appear on areas between row crops, especially if these crops tend to shade the soil and maintain abundant moisture. Under these conditions of abundant moisture and adequate light the surface algal film may occasionally become sufficiently heavy to actually interfere with water infiltration. This occurs so seldom that it is not a factor of importance. Ordinarily the algae that appear within about 3 to 6 days after a rain reach their maximum growth very quickly and soon either die or go into a resting condition. For most of the year there is not sufficient moisture present at the soil surface for visible growths to appear. These sudden bursts (blooms) of growth of the grass-green algae are greatly favored by an abundance of available nitrogen and phosphorus.

Heavy growths of blue-green algae, similar to that of grass-green algae, are seldom, if ever, seen on soils in the eastern part of the United States. This is primarily because the pH is too low and the rainy periods too short for the slow-growing Cyanophyceae to build up a visible growth. There is also some evidence that these organisms are more aquatic than the green algae. Massive blooms of blue-green algae in the spring are, however, common in fresh water ponds and lakes, rice paddies, or elsewhere if water, light and acidity are favorable, and time is not limited.

Fletcher and Martin (1948), Cameron and Fuller (1960) and Fuller et al. (1960) reported that algae and lichens (green or blue-green algae living in symbiosis with fungi) are frequently found in desert soils of the southwestern United States. They state that they appear as surface crusts on both soil and stones, and despite the extreme variations in temperature and moisture conditions, they grow rapidly during the summer rainy season. Even on cultivated soil the algae may develop crusts that are sufficiently thick as to interfere with water infiltration. These results are rather unexpected considering that the blue-green algae have very slow growth rates compared to bacteria and fungi, and desert conditions exist for most of the year. The alkalinity of these desert soils is doubtless a major factor in accounting for the observations. Furthermore, the blue-green algae have the ability to withstand very wet and very dry conditions. Spore formation is commonly observed.

Many species of blue-green algae have the ability to use atmospheric nitrogen (Lund, 1967). This fact was demonstrated many years ago by Drewes (1928), Allison and Morris (1930) and Allison et al. (1937), and has been verified by many workers since then. The workers mentioned in the preceding paragraph have also shown that several of the blue-green algae that aid in the formation of crusts on desert soils have the ability to fix nitrogen. Aside from the relatively unimportant photosynthetic bacteria, these algae are the only chlorophyll-containing plants that have been shown positively to possess this ability while living nonsymbiotically.

Diatoms comprise a vast assemblage of one-celled plants that occur in large numbers in fresh and salt water and in damp soils that are near neutral or slightly alkaline. They are unicellular algae that are surrounded by a silicified layer. They occur as solitary or free-swimming forms, or may be attached by gelatinous stalks excreted by the cells, the stalks often profusely branching. The free-swimming forms may be boat-shaped or shaped like rods, disks, wedges, etc. In the fossil form, masses of diatoms are called siliceous earths. Our knowledge of the abundance and activities of diatoms in various soils is still very meager.

The main contribution of algae to soils and plant growth is in supplying a small amount of organic matter, and not in any biochemical transformations that they bring about. This contribution is of minor importance in cultivated soils but it is likely to be of major importance in the initiation of colonization of soils that are largely barren and devoid of organic matter. On bare rocks, gravel, sand and soil, algae may initiate the process of soil formation by synthesizing food that can be used by other forms of plant and animal life. Those species that can use atmospheric nitrogen are especially valuable in speeding up the process of soil formation. Algae, like all chlorophyll-containing plants, release oxygen which, together with the nitrogen fixed from the air, are undoubtedly important factors in the growth of rice on paddy soils.

INTERRELATIONS BETWEEN MICROORGANISMS

When one studies the microflora of a soil as a whole, and also its individual parts, he is impressed by the wide diversity of the population and the close interrelations existing between the various types of organisms. This relationship is at times cooperative but more often fiercely competitive. Sometimes it seems to be neither, as when one group of organisms may remain more or less dormant for a period of time until other extremely active species have played their role. In this case playing their role usually means that they have exhausted their food supply and have no choice but to retire from the forefront of activity. Other organisms with other food requirements can then surge to the front, even if at a greatly decreased rate. These other organisms may feed on the plant and animal residues that were unavailable to the fast-growing pioneers, or they may utilize the bodies of the dead pioneers for their nutrition. It seems that in soil there is a microorganism that can attack almost every naturally-occurring product of nature, and even most artificially-produced compounds that may be added by man.

The picture presented above applies primarily to the heterotrophs that are so competitive and so important in the production of soil organic matter from plant and animal residues. True cooperation among microorganisms is, however, not a rarity. It is in a sense found even among heterotrophs, as where an organism may break down cellulose into sugars that are utilized in part by organisms that cannot attack cellulose. Similarly, a nitrogen fixing bacterium, such as *Azotobacter*, may furnish nitrogen for use by other bacteria, actinomycetes, fungi, and algae. Cooperation is even more striking between chlorophyll-containing algae and other soil organisms that utilize the photosynthetic products as their energy source. If the alga is a nitrogen fixer, it can serve both as an energy and a nitrogen source for various heterotrophs. Often cooperation, if it can be so called, takes the form of removal of a toxic compound by an organism, thereby allowing another to continue to grow. One example is the destruction of an antibiotic. Likewise, ammonia, which in excessive amounts inhibits *Nitrobacter*, may be removed by other microflora or higher plants.

This brief discussion of the microflora of soils serves to emphasize its extreme importance in almost every phase of soil organic matter formation and transformation, as well as, directly and indirectly, on crop production. Soil that appears to the naked eye to be so inert is actually at times a "beehive of activity", and the nature of the activity can markedly affect the plant that has its roots imbedded in the soil.

REFERENCES

Allison, F.E. and Morris, H.J., 1930. *Science*, 71: 221–223.

Allison, F.E., Hoover, S.R. and Morris, H.J., 1937. *Bot. Gaz.*, 98: 433–463.

Breed, R.S., Murray, E.G.D. and Smith, N.R., 1957. *Bergey's Manual of Determinative Bacteriology.* Williams and Wilkins, Baltimore, Md., 7th ed., 1094 pp.

Brian, P.W., 1957. *Ann. Rev. Plant Physiol.*, 8: 413–426.

Cameron, R.E. and Fuller, W.H., 1960. *Soil Sci. Soc. Am. Proc.*, 24: 353–356.

Clark, F.E., 1967. In: A. Burges and F. Raw (Editors) *Soil Biology.* Academic Press, New York, N.Y., pp. 15–49.

De Bano, L.F., 1969. *Sci. Rev.*, 7: 11–18.

Drewes, K., 1928. *Zentralbl. Bakt. 2. Abt.*, 76: 88–101.

Fletcher, J.E. and Martin, W.P., 1948. *Ecology*, 29: 95–100.

Fuller, W.H., Cameron, R.E. and Raica Jr., N., 1960. *Trans. Int. Congr. Soil Sci., 7th, Madison, Wisc. 1960.* pp. 617–624.

Küster, E., 1967. In: A. Burges and F. Raw (Editors) *Soil Biology.* Academic Press, New York, N.Y., pp. 111–127.

Lund, J.W.G., 1967. In: A Burges and F. Raw (Editors) *Soil Biology.* Academic Press, New York, N.Y., pp. 129–147.

Pinck, L.A. and Allison, F.E., 1944. *Soil Sci.*, 57: 155–161.

Pramer, D., 1959. *Adv. Appl. Microbiol.*, 1: 75–85.

Savage, S.M., Martin, J.P. and Letey, J., 1969. *Soil Sci. Soc. Am. Proc.*, 33: 149–151.

Shantz, H.L. and Piemeisel, R.L., 1917. *J. Agric. Res.*, 11: 191–245.

Starkey, R.L., 1925. *J. Bacteriol.*, 10: 135–163.

Starkey, R.L. and Waksman, S.A., 1943. *J. Bacteriol.*, 45: 509–519.

Warcup, J.H., 1967. In: A. Burges and F. Raw (Editors) *Soil Biology.* Academic Press, New York, N.Y., pp. 51–110.

Zaumeyer, W.J., 1958. *Ann. Rev. Microbiol.*, 12: 415–440.

Chapter 4

ANIMAL LIFE OF SOILS

INTRODUCTION

A great diversity of animals, having few morphological features in common, exists in the soil and in the litter above it. Some of these are permanent soil inhabitants, whereas others are temporary. Some are burrowing forms but others live either under surface debris or in the soil openings made by natural agencies or by man. In size the individuals vary from the microscopic Protozoa and nematodes to mammals, such as moles, rabbits and woodchucks. There are literally thousands of kinds of animals involved and many thousands of species. For example, Peters (1955) states that there are about 10,000 species of nematodes alone, half of which are free-living. The proportion of these that is found in soil is not known with accuracy, but soil nematode species are abundant. About 1,800 species of earthworms are known, and the arthropod species (principally insects) that spend a part of their lives in soils are even more numerous (Kevan, 1962).

The soil fauna play such an important role in humus formation that any reasonably complete discussion of soil organic matter and its effect on plant growth must deal with them. In the limited space available the author will refer briefly to the chief types of animals involved, mention some of the main factors that determine their abundance, and consider the role that they play in soil formation and crop production.

Soil animals are often referred to as microfauna and macrofauna (invisible and visible to the naked eye, respectively). Some investigators (Murphy, 1955) add the term meio- or mesofauna to include the intermediate sizes of about 100 μ to 1 or 2 cm in adult diameter. Kevan (1962) states that "the microfauna is composed of such animals as Protozoa, small unsegmented worms (turbellarians, rotifers, nematodes) and tardigrades; the meiofauna consists of pot-worms (Enchytraeidae) and small arthropods (pauropods and symphylids, mites, false scorpions, some spiders, Collembola and small insects), while the macrofauna includes the remaining soil animals (the larger arthropods, molluscs, earthworms and vertebrates)." For a detailed description of the species of organisms involved, reference should be made to the "key to the orders and suborders of soil and litter-inhabiting animals" (Kevan, 1955) and to the book by Kühnelt (1961) translated by Walker.

The most important kinds of animals constituting the soil and litter fauna, according to Kevan (1962), are the Protozoa, nematodes, segmented worms and the great phylum of arthropods.

INTERRELATIONSHIP BETWEEN VEGETATIVE COVER AND ANIMAL POPULATIONS

Soil-inhabiting animals form communities that are fairly stable so long as the environmental conditions remain reasonably constant. This ecological balance between organisms that have few characteristics in common is not unlike the situation that exists in plant communities. Any marked change in the environment may, however, radically modify the animal community. Some kinds of animals may be eliminated entirely, or at least the ratio between individual kinds within the community may be changed markedly (Tischler, 1955).

Each kind of animal, like other living things, has its own optimum environment. It happens, however, that with few exceptions, such as special food requirements, most of the animals of special interest from the standpoint of soil organic matter are affected somewhat similarly. This can best be illustrated by reference to what happens to the animal community when man modifies rather radically the environment that nature provided.

Animal populations, including both the true soil forms and the litter dwellers, are likely to be highest in a region of abundant rainfall and where the soil is covered with a heavy growth of vegetation. Leaves of herbaceous trees and shrubs, legumes, grasses and other plants that supply a mass of easily digestible residues to the soil each year furnish the food that the fauna need. This litter also helps in the retention of soil moisture and acts as a protection for numerous types of animals, especially the arthropods that spend only a portion of their life, or life cycle, in the soil-litter environment. Under natural conditions neither the soil nor the vegetative cover is disturbed. Although many of the animal types may live wholly in or just beneath the organic layer, there are always at least a few animals that will burrow into the soil mass. And when excavations are once made, or the soil becomes channeled either by burrowing animals, by tree roots that eventually die, or by other means, the way has been opened for non-burrowing animals to invade the soil mass.

High animal populations are favored still further by the accumulation of tree limbs, logs and stumps that furnish protection for various kinds of animals and food for the wood-eating insects. Rotting stumps and partially buried logs furnish an ideal environment for animals, and such protection is especially important to them during periods of drought or extreme cold. They also serve as recolonization centers if for any reason most of the animal population of a given area happens to be killed.

The following description by Jacot (1935) of animal life on the forest floor is very colorful and expressive. "Deer, jumping mice and the oven-bird are denizens of the forest floor by virtue of using it as their substratum, but there is also a host of curious animals which use the forest floor, especially the litter of dead leaves, twigs, branches and fruit parts, as their walls, ceiling and subbasements. Looked at from the eye level of the cockroach, this litter becomes a several-story edifice of enormous extent. The various floors are separated by twigs, midribs, petioles, fruit husks, samaras, skulls, elytra and feces. The lower one descends, the more compact is the structure. The leaves become more fragmentary, the feces of worms, which have come up from the soil, of caterpillars which live in the trees and of the inhabitants themselves, as well as grains of sand brought up by the worms and heterogeneous assortment of ant and beetle skulls and wing covers, become more abundant. This complex is rendered more intricate by the growth of minute fungus moulds which feed upon the dead leaves and organic refuse, weaving it all into a compact mat by their myriad white hyphae. Thus is the woof woven into the warp of the woodland rug."

When a virgin deciduous forest on a mull soil, heavily populated with soil and litter animals, is cleared there occurs a sudden and marked change in the fauna. Many forms of animal life may disappear entirely and the others decrease in numbers to a fraction of the original population. The change is especially violent if the brush is burned and the soil is left bare. If the clearing is seeded to grasses, the animal population is gradually restored in part, although the composition of this new animal community may be very different from the original. Heavy grazing of the grassy areas will retard the comeback of the animal population because of compaction and prevention of accumulation of a decaying plant cover on the soil. Grasslands that are only lightly grazed, or are mowed only occasionally, are likely to be well populated. In such areas soil-inhabiting animals, such as earthworms, are very much favored if the soil is a clay or loam and not too acid. Wood-eating insects are absent.

In permanent grasslands on fertile soils there is usually a dense network of roots in the surface 1 to 4 inches. This layer is very porous and absorbs water so readily that runoff is at or near zero except possibly on very steep slopes. In these grasslands there is always at least some covering of organic debris that serves both as a mulch and as a food source for microflora and fauna. Normally these fertile grasslands are well populated with earthworms, and their numerous casts serve further to provide the porous surface that is so desirable. It is in this surface portion of the A-horizon, matted with living and dead roots, that the animal population is concentrated. Aside from earthworms, there is usually an abundant population of nematodes, crickets, grasshoppers, snails, mites, a wide variety of other insects, numerous worms of all kinds, and even some rodents.

When grasslands are ploughed up and subsequently used for the growth of cultivated crops, masses of the soil animals are killed. This results in part from the damage caused by the plough and tillage instruments but more importantly by the radical change in the environmental conditions. The protection afforded by the tops and roots of the grass, including the dead portions, is removed and the habitat of the animals thereby radically changed. Their food supply is largely exhausted, the mass of roots is no longer present, and the soil is now subject to drying out and more rapid temperature changes. The animals that do not die are now dependent upon tilled crops for their food, and these crops have much smaller surface root systems. Much of the plant substance that is produced is not returned to the soil but is removed in harvested crops. Earthworms may be able to continue a reasonably normal life but many of the soil animals cannot survive. If they do, they may feed on the living roots of cultivated plants and do considerable damage. This applies especially to many insects that find arable lands and cultivated crops very much to their liking. Many of these pests are not important inhabitants of either woodlands or pasturelands.

The frequent ploughing and tilling of arable lands is very harmful to non-burrowing soil animals that live in soil pockets, root channels and other crevices. In cultivated soil there is no permanency; any animal population that may be established is likely to be temporary. If eggs are laid in soil crevices they may be destroyed through tillage, drying out, or excess temperature. The microfauna may not be injured severely but certainly there are radical changes in composition of both the meso- and macrofauna. Crop rotation is a serious factor that affects markedly the animal community.

Our knowledge of the effect of various cultural practices on the soil population is still very inadequate and largely of a qualitative nature. Many of the new insecticides, and possibly also herbicides, that are constantly being introduced are undoubtedly exerting a considerable effect on different portions of the soil population, but quantitative data on this subject are largely unavailable.

SOIL ANIMALS – THEIR ABUNDANCE AND ACTIVITIES

The soil animal population that is of most agricultural interest is that of arable soils, including grasslands, and the discussion that follows will therefore deal primarily with this fauna. Little or no reference is made to numerous genera that are either of minor agricultural importance, or which have little contact with the soil during their life cycle. The soil animal population is commonly divided into two general classes, namely, those that are not insects and those that are insects or insect-like (arthropods).

Animals other than arthropods

Protozoa

Soil Protozoa commonly vary in size from about 5 to 100 μ in diameter, being smaller than fresh water forms. They exist both as motile and as encysted resting forms. Some are amoeboid, others are oval with cilia, and still others are small irregularly-shaped organisms that propel themselves by means of flagella. Their food consists chiefly of bacteria but some species can also digest other organisms, including Protozoa. Plant and animal residues are utilized to at least a minor extent. Protozoa are aerobic organisms that require a moist soil for growth and thrive best in neutral soils well supplied with animal manures or other forms of organic matter. Although there is evidence that soils contain Protozoa species that have adapted themselves to this basically unfavorable environment, this form of animal life must be considered as essentially aquatic.

Considerable work has been done in an attempt to estimate the Protozoa populations in soil but we still have only a partial picture of these animals. Usually numbers of organisms have been estimated by means of culture techniques that record both the active and encysted forms. Since there is general agreement that encysted forms greatly outnumber the active forms in most arable soils, it is obvious that such data tell us little about the activity and importance of Protozoa in soils. The composition of the protozoan fauna seems not to vary greatly from soil to soil but the mass of organisms is seldom large. Stout and Heal (1967) state that "it seems likely, therefore, that in most temperate arable and grassland soils there is a comparatively small biomass, less than 5 g/m^2, but that in woodland soils or in cold grassland soils where there is accumulation of organic matter and conditions favoring the relatively large species of rhizopods, both amoebae and testacea, the biomass of Protozoa may be appreciably greater, possibly up to 20 g/m^2." But the question arises: is any appreciable amount of this biomass active in soils at times other than when moisture is very abundant?

Stout and Heal summarize the morphological and physiological characters that appear to favor the existence of Protozoa in soil as follows: "Small size and simple structure; a capacity for rapid multiplication under favorable conditions; encystment and excystment mechanisms adapted to fluctuations of soil moisture, salinity, aeration and food supply; tolerance of a wide range of pH and temperature; the ability to absorb nutrients in dissolved or particulate form." The rhizosphere of plants is a favorable environment for Protozoa because of the increased food supply in the forms of bacteria, plant excretions and plant residues. Although soil Protozoa can feed on a wide range of bacteria, they can apparently exercise a choice as to the species that they prefer.

Extensive microscopic and cultural studies by the writer made several years ago (Fellers and Allison, 1920) led to the conclusion that Protozoa are of minor importance in normal soils; at least that was true in the state of New Jersey where the work was done. A total of 104 species was isolated from soils and identified but they existed almost wholly in an encysted or resting stage. Only two soils out of a hundred samples taken all over the state showed the presence of living, motile Protozoa on direct examination. Limited numbers of active organisms were found in soils taken from ditches, poorly-drained areas, or a few days after a rainy period. These findings are not in agreement with the findings of some other workers who have used less normal soils, such as greenhouse soils or those treated with sewage. It is believed that the New Jersey data are representative of conditions found in most arable soils of low to medium organic matter content, and where the rainfall is in the order of 40 inches per year. No more recent data have appeared that would lead this author to any conclusion other than that previously arrived at, namely, that Protozoa are of minor importance in the large majority of soils. This applies to their contribution to organic matter breakdown and to the overall effects on crop production. Admittedly, quantitative data are very inadequate, but the qualitative information seems to indicate that, under the most favorable conditions for Protozoa, they are not sufficiently abundant and active to have much effect on the bacterial population and on the decaying organic matter on which they feed. For additional information on soil Protozoa, reference should be made to publications by Franz (1950), Thornton and Crump (1952), Singh (1955), and Stout and Heal (1967).

Nematodes (Nematoda)

Nematodes, or eelworms, are abundant in nature, being widely distributed as parasites of vertebrate and invertebrate animals, and of plants. Free-living nematodes also constitute an important part of the soil fauna, being more numerous than any other animal of comparable size (Christie, 1959). Nielsen (1967) states that there are about 10,000 known species of Nematoda but of these only about 2,000 are soil inhabitants. These soil species are for the most part of microscopic or near-microscopic size, whereas the animal parasitic species are mostly visible to the naked eye. The average length of the kinds that occur in soil is about one millimeter.

According to Nielsen, soil nematodes are restricted to habitats with a saturated atmosphere since water is readily lost through their permeable cuticle. This means that they live primarily in the water films covering the soil particles, and on or in plant roots. He states that they are "typical members of the interstitial fauna of soil, along with Protozoa, rotifers, gastrotrichs, turbellarians and tardigrades." Nematodes are active in moist soils but not in soils that are at or near the wilting point (pF4). Most species seem to be able to withstand repeated desiccations and resume activity when the moisture supply permits.

Most soil and plant nematodes have a simple life cycle. The females lay eggs that hatch into small larvae resembling the adults. As these young grow they undergo four molts or larval stages before reaching the adult stage. In some species there is considerable difference in size and shape of the male and female, the latter usually being larger, and often saccate rather than eel-shaped.

Christie places soil-inhabiting nematodes into three groups, based on their feeding habits. These are: (1) saprophagous species that feed on decaying organic matter or on the microorganisms associated with decay; (2) predaceous species that feed on small animals, including other nematodes; and (3) species that feed on higher plants, algae, fungi and other low forms of plant life. Most any part of a higher plant may be attacked, but the roots and other structures below ground are the chief food sources of this third group. Nematodes are not highly specialized with respect to the plant species upon which they feed.

Some plant nematodes feed primarily on the outside of plant tissues whereas others are chiefly internal feeders, although there is no sharp line of demarcation between the two groups. The stubby-root nematodes, for example, are largely external feeders but the young larvae are sometimes found within young roots. The root-knot nematodes are primarily internal parasites but even in this case the young may feed to some extent externally. Larvae of both sexes of the root-knot nematode penetrate the roots and undergo similar development. A few nematodes feed on the buds, leaves and stems, but most species feed on the underground plant parts.

The important features of nematode nutrition, according to Nielsen, may be summarized as follows: "(1) the food of nematodes seems, invariably, to be 'protoplasm', be it obtained as cell contents, plant sap, the contents of fungal hyphae, algae, bacteria, actinomycetes, Protozoa, or animals; (2) the dead organic matter and plant remains of the soil play a considerable role as a substratum for the organisms on which nematodes feed, but do not form part of the nematode diet." He states further that substances normally associated with cell walls and skeletal structures are usually not ingested or are only present in negligible amounts.

Plant nematodes characteristically have a stylet or spear at the anterior end which they use in various ways, one being to puncture cells and suck out the contents. The nematodes commonly begin their attack on plant tissues by injecting through the stylet a secretion that digests the cell contents. The secretion of the root-knot nematodes also serves to modify the development of the surrounding plant cells. The nematodes then feed on the newly developed tissues.

How important are nematodes from the standpoint of organic matter breakdown and humus formation? This question cannot be answered in any very positive way based on quantitative data. There are at least three major reasons why this is true. First, the science of soil and plant nematology was one of the last of the biological sciences to be established as an independent branch apart from other disciplines. For many years most universities did not even offer courses in nematology, and even today the number of nematologists active in research is comparatively small. Second, the research that has been done in recent years has been largely concentrated on the nematodes that attack growing crops, and these species are numerous and the damage great. Most of the information that we now have on free-living, non-parasitic nematodes has been obtained more or less as a by-product of studies of plant nematodes. This information is largely qualitative. Third, any attempt to obtain quantitative data on the contribution of nematodes to humus formation, and to the broader subject of soil fertility, would be fraught with essentially insurmountable difficulties. The breakdown of plant materials in soils involves a whole spectrum of organisms. The remarks of Nielsen, mentioned above, indicate that nematodes play only a minor role in organic matter breakdown, since they do not feed to any great extent on dead plant tissues. They do, however, actively feed upon microorganisms that live on decaying plant tissues and thus affect total microbial activity and ecological relationships.

The conclusions of Franz (1950), who has made extensive studies of the soil fauna in Europe, are worthy of note. He states that nematodes are present in most soils in very large numbers, 10–20 millions per square meter to a depth of 10 cm (70–140 per g). Most of these are not pathogenic, and many are predacious on pathogenic species. He states further that as the weight of the nematodes is small, it is doubtful whether they play an important role in the transformation of soil organic matter. Jones (1959) also considered that nematodes are relatively unimportant in the economy of the soil. This is due in large part to their dependence on water which makes the soil environment rather unsatisfactory.

Earthworms (Lumbricidae)

Earthworms are the most obvious fauna in soils, frequently comprising more than half of the biomass present. They are found widely distributed in moist soils that are not more acid than about pH 4.5 and which are capable of good crop production (Guild, 1948; Satchell, 1955). According to Satchell (1958) there are about 28 species in Britain of which 8–10 species are commonly found in field soils. A few additional species are found in Australia, India and Africa. Nielsen and Hole (1964) have indicated that the number of species in the world may be as high as 1,800. Most of the more important species are widely distributed as a result of human activities over the years. They have been studied rather intensively by zoologists but our information on their activities and benefits to agriculture is still incomplete in many respects (Murphy, 1953). The factors that determine which species will be dominant at any one location, where several species may be present, are also not well understood (Guild, 1948; Gerard, 1963).

The larger species of earthworms common in the United States and Europe, such as *Lumbricus terrestris*, have a length of up to about 25 cm. Other smaller, and usually more abundant forms, may be only one-tenth this long. In weight, the variation may be from about 0.05 to 5.0 g per animal. Walton (1935) states that in Africa, Ceylon, and Australia earthworms have been found that are 3–9 ft. long. Fortunately, they have not gained a foothold elsewhere. For more information on the characteristics of the various species and their activities reference should be made to Kevan (1955, 1962), Satchell (1958, 1967), Barley (1961), Kühnelt (1961), Russell (1961) and Doeksen and Van der Drift (1963).

In studies of earthworm activity in forest soils of Wisconsin, Nielsen and Hole (1964) estimated that the total live weight of earthworms per acre was 1,980 lb., more than half of which was the imported *L. terrestris.* They state that this species is "changing the process of incorporation of organic matter into the soil with accompanying changes in soil microclimate, erosion, condition of seedbed, rate of nutrient cycling, and depth of A-horizon."

The biomass of a grassland population of approximately a million earthworms per acre has been estimated at about 500 lb. (Satchell, 1958). Population densities vary extremely widely in soils but values of a half million per acre have been recorded frequently. A few workers have reported as many as 4–7 millions per acre. The populations of arable lands are usually considerably below those of old grasslands. Guild (1951) made counts of earthworm populations in Scotland over a 6-year period and found approximately 400,000 per acre in sandy soil, 250,000 in loamy soil and 100,000 in a clay soil. In garden soils of high organic matter content he considered that populations of 1,000,000 would be expected. Most workers have reported higher numbers in medium-textured soils than in either very sandy or clay soils (Guild, 1948).

Earthworms are basically aquatic organisms but can withstand severe desiccation and remain in a quiescent state for months. It has been stated that movement and burrowing cannot proceed normally if the water content of the body falls by more than 18%, but they can survive a loss of 70–75% of their normal water content. Because of sensitivity to moisture and temperature earthworm activity is very seasonal.

The food of earthworms consists of organic matter, both animal and vegetable, but primarily the latter. Some species live in decaying vegetable matter, such as leaf litter in forests, or in manure and compost piles, and seldom penetrate the soil to any appreciable depth. Other species, such as *L. terrestris, Allolobophora nocturna*, and *A. longa*, live in the soil but commonly come to the surface to feed. Most of their activities are concentrated in the first 8 inches of soil into which they drag vegetable matter. In dry periods they may construct channels to a depth of three feet or more where they remain in a semi-dormant condition until soil moisture and temperature are favorable. These larger species swallow great quantities of earth, from which they digest much of the organic matter and discard the mineral matter and undigested organic residues as casts on the soil surface. Other species commonly discard below ground most or all of the soil that they ingest. Earthworms are somewhat selective, if given a choice, in the vegetable matter that they eat. They prefer the more tender and nutritious plant materials including leaves of trees, succulent grass clippings, manure, and residues of garden crops. They may at times feed to a limited extent on plant roots but for the most part living and growing plants are not attacked, probably because of their inability to do so. There is little or no evidence that they are responsible for any appreciable injury to garden crops, except possibly to an occasional seedling. And yet it is in heavily manured garden soils that their numbers are likely to be greatest.

Earthworms are aggressive competitors for food and when the supply is limited the worm population is likely to show a close correlation with the quantity and quality of the food available if other environmental conditions are favorable. As is true of most other organisms, protein is much needed.

Barley (1959b) found that a population of *A. caliginosa* consumed 200–300 mg dry weight of earth per g body weight per day. Passage through the gut required about 20 hours.

The digestive apparatus of earthworms is equipped with a gizzard-like organ that enables them to grind up the tougher portions of their food. These animals have no teeth or other apparatus for biting or gnawing, but do have powerful muscles and other equipment that enables them to suck or grasp their food and pull it into their soil channels.

The quantity of soil ingested by earthworms in a year may be surprisingly large. It was Darwin (1881) who first called attention to this fact. In some fields he observed that worms bring 0.2 inches (about 30 tons per acre) of soil to the surface per year over a 25-year period and in the process bury stones, cinders and other foreign bodies. Keith (1942) re-examined the fields that Darwin had studied, and found that the cinders that he had spread a century earlier were there, but had not continued to be buried deeper and deeper by worm action, but had reached a stationary level. This is in harmony with expectations, based on present knowledge, since most of the worm activity is now known to be in the top 8 inches of soil. More recently Evans (1948) estimated that the earthworms in pasture land at Rothamsted ingested 5–9 kg of oven-dry soil per square meter per year. This corresponds to about 22–39 tons per acre – values that agree closely with Darwin's earlier estimate. Not all of the soil that worms ingest is brought to the surface since, as already stated, some species do not come to the surface to deposit casts. It should also be emphasized that these values represent maximum values; many arable soils may have populations that are only a fraction of those in permanent grasslands. In studies made by Barley the soil brought to the surface yearly was the equivalent of only a layer 0.2 mm in thickness.

The environmental conditions required for good activity of earthworms include abundant moisture, good aeration, a temperature above freezing, a near-neutral soil, adequate calcium, and a plentiful supply of nutritious organic matter. They prefer a loam or clay soil that is well aerated, but can by their own activities improve the structure, drainage and aeration of clay soils that are not entirely suitable for their growth.

Barley (1959a) observed that in a 4-year rotation of two years of grass, one of fallow and one of wheat, the weight of the worms after the fallow and crop years was only a quarter of that found on permanent pasture, but after the grass the weight almost equalled that on permanent pasture.

The above discussion of earthworms emphasizes that they can often be of major importance in the consumption of organic matter, in the mixing of it with soil, in soil aggregation, and in fact in almost all phases of humus formation and interactions in soil. It is well established that under favorable conditions, as in permanent pastures, earthworms are the principal agents in mixing surface plant residues with the main body of the soil. For example, Russell (1961) points out that at Rothamsted on soils having pH values of less than 4, and which do not support a population of earthworms, a mat of dead vegetation is accumulating. This does not occur on neutral soils. Animals other than earthworms are also affected by high acidity but undoubtedly it is the earthworms that are the main fauna involved in the removal of the surface litter. As digestion and decomposition proceed, nutrients are released that crops may utilize. The worms accelerate the release.

Kleinig (1966) also states that in Australia on irrigated pastures and under dryland conditions where fauna are largely absent, mats of partially decomposed organic matter may accumulate to a depth of an inch or more. Mat weights were observed to range from 8,000 to 9,200 lb. per acre, and contained 85 or more lb. of nitrogen. Such mats may retain up to 0.6 inches of water after irrigation.

Satchell (1967) emphasizes the role that earthworms play in organic matter transformations and concludes that "on present evidence, conditioning plant remains for microbial decomposition seems to be the most important action of Lumbricidae in the ecosystem." Certainly these animals do increase the rate of decomposition of crop residues, and also have some effect on the ecology, but whether these effects are of greater importance than the effects on soil physical properties may be debatable.

The effect of this activity on soil aggregation and tilth is discussed in Chapter 16.

Potworms (Enchytraeidae)

The Enchytraeidae are widely distributed, but because of sensitivity to drought they are most abundant in moist temperate climates. Their habitats may be the soil, water, or litter, depending upon the species. The soil forms are most abundant under acid conditions and where the content of organic matter is high.

Potworms are white and vary in size over the range of less than 1 mm in length to 5 cm (O'Connor, 1967). There is some difference of opinion as to their ability to burrow into soil, but it seems likely that any such power is limited, and that they usually use existing crevices. Certainly any burrowing that they do is almost infinitesimal in comparison with earthworms.

The number of these worms in soil varies widely, being least in summer when soils tend to dry out, and greatest in the fall. Nielsen (1955) found 2,000–10,000/m^2 in arable soil in Denmark and up to 100,000 in natural undisturbed soils. Others have reported populations as high as 250,000–300,000/m^2 in forest and moorland soils (O'Connor, 1967).

Little is known about the feeding habits of potworms, but we do know that various species ingest plant debris, fungi, bacteria, algae, and sewage. Along sea coasts they feed on seaweed and decaying animal tissues. There is some evidence that they can feed on nematodes. How much of the decomposition of these materials is brought about by the potworms and how much by the microflora that is always present is not known. O'Connor states that "in any event it is apparent that the long accepted generalization that the soil-dwelling Enchytraeidae are primary decomposers of plant litter is untenable." He also states that the role of these organisms in the development of humus is but little understood. Their growth requirements and habitats would seem to indicate that they are not very important in soil organic matter transformations under arable soil conditions.

Rotifers and flatworms (Rotatoria and Turbellaria)

Rotifers are small worms that are found abundantly in woodlands and meadows in or under the layer of decaying organic matter or moss. About 100 species have been described (Kevan, 1962). Like the nematodes they require a water film in which to move and grow. Some can withstand drought whereas others cannot. The food of some species consists largely of plant debris and algae; others are predacious on Protozoa, nematodes and bacteria. Little is known about their activities in soils but they are apparently of very minor importance.

Flatworms are inhabitants of well-drained woodland soils and decaying leaf masses. One species, which may attain a length of 10–15 mm, crawls like snails on a slime ribbon. They feed on nematodes, rotifers, and other small animals. Since they require moist soil and organic matter it is unlikely that these worms or wormlike animals contribute much to agriculture in either a positive or negative way.

Slugs and snails (Mollusca)

Slugs and snails are the two gastropods of most importance in soils, but are for the most part not true soil dwellers; they occur mostly on the soil surface. They thrive under very moist conditions and are likely to be most abundant where they can hide under plant cover, stones, etc. Snails prefer woodlands or wherever there is surface debris to furnish protection. Slugs also abound under such conditions, but are very frequently present in cropped land in numbers such as to cause much damage (Brown, 1955).

Aside from food and shelter, lime and moisture are the chief ecological factors that determine distribution. The animals with large calcareous shells require much calcium in their diet which is inadequately supplied by plants that grow on acid soils. The harmful effect of soil acidity is therefore indirect and not direct (Newell, 1967).

The food of gastropods varies with species but for the group as a whole includes a variety of commercial crops, many annual flowering plants, weeds, underground storage organs, algae, lichens, fungi and various plant parts in the initial stages of decay. Some species feed on earthworms and other animals, or on the carcasses of dead animals.

Slugs are very important pests and difficult to combat. Wheat, potatoes, vegetable crops and flower gardens frequently suffer severe damage. The damage is likely to be great in wet seasons and mild in dry years. Characteristically, they hide by day to protect themselves from the sun and wind, and spend their nights feeding. Young, tender plants may be almost stripped of many of their leaves within a period of a few days. The young newly-hatched animals seem to be responsible for most of this damage. In my own garden, attempts to grow pansies and some other flowering plants near a loose rock wall met with complete failure although plants at a distance of ten feet or more were almost unharmed. The feeding range of these animals is comparatively limited.

In his discussion of the possible role of slugs and snails in soil formation Newell states that "soil animals are widely considered to be important in disposing of litter and to affect the crumb structure by passing soil through their guts; which in turn influences the aeration and water retaining capacity of the soil. Inasmuch as snails and slugs also feed on vegetation and produce partially digested plant material and mucus they also may have a similar function. The large numbers of land molluscs in some soils may modify their soil environment. Like earthworms they produce mucoproteins both with their faeces and during crawling, which may bond small soil particles together to form a well-defined soil crumb structure." Although the ingestion of plant materials by slugs and snails increases the rate of decomposition, there is little evidence that the effect on soil aggregation is little more than temporary. When the mucoid cementing substances have been decomposed by the heavy bacterial populations always present, especially in the feces, the unstable aggregates soon disappear. Organic cements alone seldom, if ever, produce stable aggregates (see Chapter 16).

From the standpoint of soil humus formation, slugs and snails are of considerably less importance than are earthworms, because most of their activities are confined to the soil surface. They carry little of the vegetation into the soil beyond the upper one or two inches.

Vertebrates

Numerous species of mammals are common part-time inhabitants of soil. They often play a small but important part in soil formation by their excavations, which are accompanied by the transport of organic matter into their burrows. Such animals include rabbits, woodchucks, muskrats, prairie dogs, rats, mice, chipmunks and several other small animals. Most of these line their nests with plant materials. The total amount of subsoil moved to the surface, and of plant substances carried into their dens, is not large but over a period of years can undoubtedly have a considerable effect on soil formation. Such an effect would likely be greatest in undisturbed forest and waste lands, and in grassed areas.

A few animal species spend most or all of their life in the soil. Of these the common mole is probably the best known. In addition, Kevan (1955, 1962) mentions the rodent-moles of Europe and Asia, mole-rats of Africa and South America, salamanders, and the naked mole-rat or faranfat. Some of these, such as the common mole, excavate their burrows and underground passages, but the rodents may merely use existing channels. Whether carnivorous in their feeding habits, like the mole, or vegetarian, like most rodents, they all help to get organic matter into the soil, even if slowly. When these various animals are present in cropped areas, the damage that they do to crops may be considerable but fortunately most of them, other than the common mole, are not abundant in arable soils. The mole may be either beneficial or harmful. It does help in getting plant materials mixed with the soil and in improving aeration, but in a vegetable garden it can do much damage by undermining the young seedlings and causing them to die as a result of root disturbance and drying out of the soil.

In his discussion of the biological importance of soil fauna, Mellanby (1960) states that "moles are among the most active mammals, and they die of starvation unless they eat their own weight of food, largely earthworms, every 24 hours. Thus a four-ounce mole may consume a hundredweight of worms in a year. Moles have a high metabolic rate and four moles (total weight one pound) may be considered to have the 'biological equivalent' of 1,000 lb. of earthworms." One might ask what do the moles live on during six months of the year when earthworms are not active, or even in the summer during periods of drought? Mellanby states further that moles seldom reach a permanent density of four to the acre, even in grasslands, but "two moles can bring a greater weight of soil to the surface in 24 hours than can a whole population of earthworms with a total body weight of nearly half a ton." I would question this statement, because in years of observations of mole activity in Indiana I observed populations considerably greater than 4 per acre, and I saw little evidence of extensive molehill formation; their chief activity under my conditions of observation was in building long runways in newly-plowed land immediately following rains.

Several other vertebrate animals including birds, snakes, lizards and tortoises may live in or on the soil for a part of the time. They are indirectly important in that they eat many animals, especially earthworms and insects, that are soil dwellers.

Arthropods

According to Kevan (1962) a high proportion of the animal population of the soil consists of arthropods, chiefly insects. Kevan (1965) states that "the most abundant soil arthropods are the mites (Arachnida, Acarina), and the springtails (Collembola). Also very important are the millipedes (Diplopoda) and certain orders of insects, particularly termites (Isoptera) where they occur, fly larvae (Diptera), beetles and their larvae (Coleoptera), and ants (Hymenoptera, Formicoidea). Other groups of lesser importance, which may nevertheless be conspicuous, are woodlice (terrestrial isopod Crustacea),

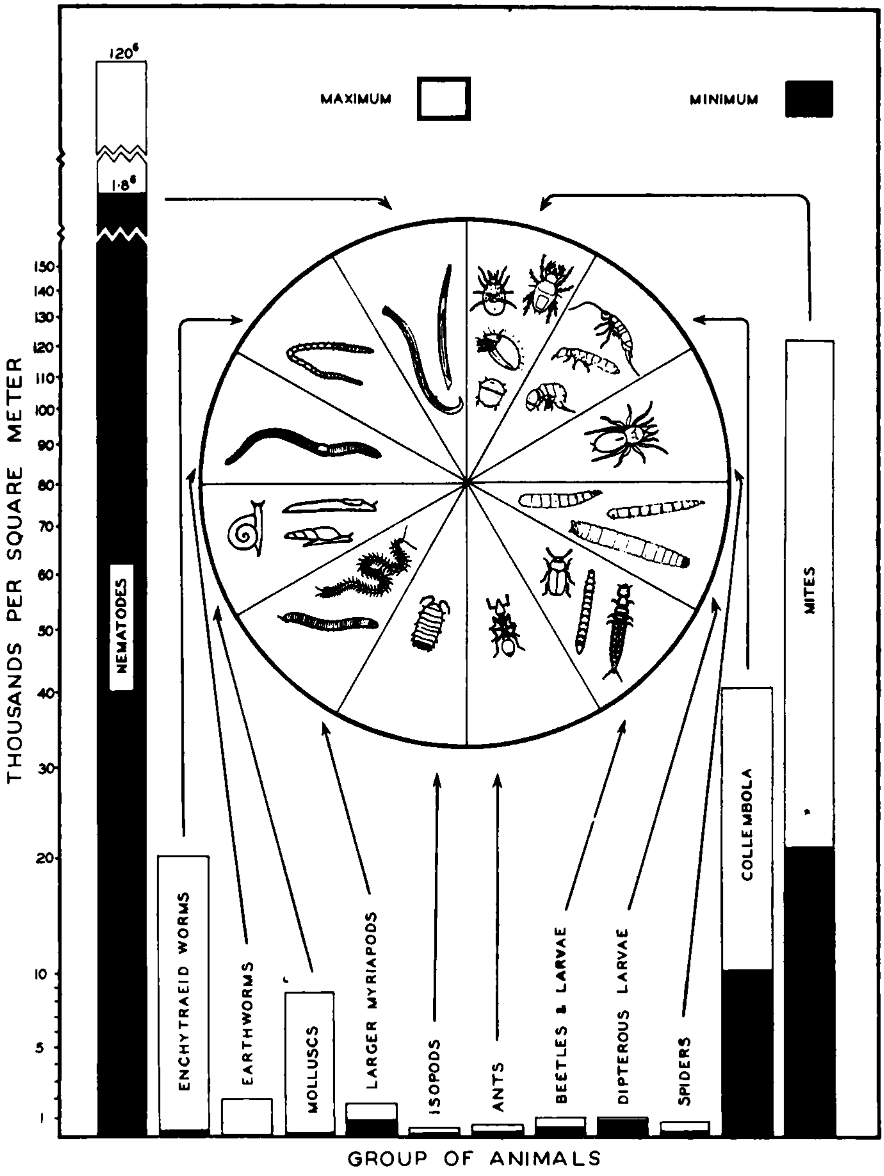

Fig.4.1. Numbers of animals per square meter in soil of a European grassland, plotted on a logarithmic scale. (From D. Keith McE. Kevan, 1965. Originally published by University of California Press, Berkeley, Calif., reprinted by permission of the Regents of the University of California.)

centipedes (Chilopoda), cutworms and other caterpillars (Lepidoptera), root-feeding bugs such as cicadas, aphids, and scale insects (Hemiptera–Homoptera), burrowing crickets (Orthoptera), and spiders (Araneida). Protura and Pauropoda are minute arthropods which may be locally very numerous. Many other groups of both larger and smaller size are also represented to a varying degree." Fig.4.1, taken from Kevan (1965), gives an idea of the numbers of the various groups of organisms as determined on one square meter of a European grassland. Kevan (1955) and Raw (1967) give much information on the nature and feeding habits of the various types of arthropods.

Most of these animals, other than the ants, termites, and some beetles, do not penetrate the soil to any great extent, but live in the surface litter and in existing crevices in the soil, or in channels made by plant roots, earthworms and other animals. Many of the insects may lay their eggs in or under litter and after hatching spend their larval stage in this environment. It has been estimated that 95% of all insects live in the soil for at least brief periods during their life cycles.

The food habits of these arthropods are so varied that about the only general statement that can be made is that there is essentially no form of vegetable or animal matter that is not consumed by one or more of these species. Many of the insects multiply rapidly and consume enormous quantities of living and dead plant material, especially the former. The larval forms and some adults may attack the roots and thereby injure plants, but most of the damage is done by the larvae and adults when they feed on the tops of plants.

The importance of these forms of animal life, considered as a whole, in the transport of vegetable matter into the soil, in humus formation and in soil structure improvement is not nearly as great as the contribution of earthworms, for example. This is largely because of where and how they live, and what they eat. Casts consisting of soil and organic matter intimately mixed, are not produced to any appreciable extent. Some beetles do transport considerable animal manure into the soil but this type of beetle is usually not abundant, and they are of importance only in pastures. In general, the damage that arthropods do to growing crops is far greater than any benefits that result from their speed up of the humification process. They must not, however, be ignored in a consideration of the whole humification process. The more important of the arthropods are considered below.

Mites (Acarina)

Mites constitute one of the most ubiquitous and numerous of the animal groups. Their numbers are legion and according to Evans (1955) they outnumber all other groups of soil arthropods together by more than three to one. Most of these organisms are very small, free-living, soil- and litter-inhabiting species, and many of them are predatory. According to Wallwork (1967), four of the seven Orders of Acari, namely Cryptostigmata, Mesostigmata, Prostigmata and Astigmata, are generally represented in the soil fauna. He considers the classification, distribution, feeding habits and metabolism of these various types of organisms in some detail.

The Cryptostigmata are the most numerous of the four groups. They thrive under moist soil conditions. Their food habits are varied and differ markedly with the species, and even within a single species. Some feed on decaying organic matter whereas others attack underground living tissues, particularly injured bulbs, etc. Fungal hyphae and spores, various microorganisms, insect eggs and animal remains are other common food sources. Woody tissues including twigs, bark and leaves are the preferred food sources of several species. Some of these mites are now believed to be important agents in the spread of root rots and other plant diseases.

The Mesostigmata are largely predators on nematodes, potworms and other arthropods; other species feed on dead animal remains and fecal matter. Undoubtedly some of these mites feed largely on fungi and other microorganisms. Many of these are comparatively large and active with mouthparts adapted for piercing, sucking and tearing.

The Prostigmata also include species that are predatory on insect eggs, nematodes, and other arthropods. Other species are fungal feeders and a few live on green leaves and pollen. Our knowledge of the habits of the species of this Order is still limited.

The Astigmata have also not been adequately studied but according to Wallwork they are believed to feed on plant detritus, fungi, algae and the liquified products of putrefaction processes. They are commonly associated with drier conditions and are not very important elements in the acarine fauna of most soils.

Metabolism studies made of the Acari, as well as our general knowledge of their distribution and food requirements, seem to indicate that they play a comparatively unimportant role in the direct decomposition of litter. Wallwork cites research showing that the metabolism of Cryptostigmata mites accounts for only 1.8% per annum of the total soil metabolism of a forest soil. Only a small amount of this metabolism would contribute materially to humus formation. Sugar oxidation, for example, produces carbon dioxide and water and not humus. Mites do accelerate decay through comminution of plant remains, through distribution of fungi and bacteria, and through the transport of products of decomposition to lower parts of the soil profile.

Springtails (Collembola)

Springtails are usually classed as insects but they are not very closely related to true insects. Although less numerous in soils than are the mites, they have a world-wide distribution and constitute the bulk of the remaining arthropod fauna. Most of them are more soil-inhabiting than are the mites but several species spend most of their lives above ground. These above-ground forms may reach a length of 6 mm but the soil forms are seldom more than one-fourth this length. On the basis of inadequate studies we know that the springtails as a group eat a wide variety of foods including decaying plant materials, fungi, animal remains, feces of other soil animals, and humus. A few species are predatory at times but these are the exceptions. Hale (1967) summarizes the results of recent research dealing with this group of organisms.

Myriapods

The myriapods include millipedes, centipedes and symphylids, all of which are essentially soil animals.

Millipedes (Diplopoda) are commonly found in woodlands both in rotting wood and in the ground but they leave this environment to feed on living and dead plants, which together with fungi are their main food source. Most of the adults can burrow into soil or litter but the young must depend chiefly on pre-existing crevices for entrance into the soil. Newly-hatched animals usually have six legs but acquire more as they grow older.

Centipedes (Chilopoda) are medium-sized to large carnivorous animals that are found chiefly in woodlands but also in grasslands and arable soil. Some species can burrow readily, whereas others must depend on cracks or crevices for entrance into the soil. They may frequently be found in surface litter or under stones or rotting wood. They will kill and eat almost any of the soil animals common to garden soils. According to Kevan (1962) the number of legs on the adults of different species may be in the range of 16–173 pairs.

Symphylids (Symphyla) are white, active, centipede-like animals, usually less than a centimeter in length. The adults have twelve pairs of legs. They are common in the upper layers of organic soils where the humidity is favorable. They are not burrowing animals but depend on soil fissures or crevices. Their common food consists of dead plant material but they may also attack living roots. Some species are severe plant pests where conditions are especially favorable for their multiplication.

Termites (Isoptera)

The majority of termites are tropical or sub-tropical, although a number of species occur in temperate climates. There are three kinds of soil-inhabiting termites: namely, wood-feeders, fungus-growers and humus-feeders (Harris, 1955). Some of the species in the tropics build mounds that may reach a height of several feet (Nye, 1955). Those that are common in the temperate regions of the United States usually live in the ground and build tunnels out of earth or feces leading to their supply of wood. Sometimes they make their homes within decaying logs. Termites are of importance in connection with soils because they may bring up soil from a depth of 3–10 ft. (Raw, 1967). Coarse sands and gravel are not transported to the surface but only the particles less than about 1–2 mm. Probably a considerable portion of the clay and silt particles passes through the gut in the process of transportation from the lower depths.

Cellulose is the main carbohydrate utilized by termites that feed on wood or vegetable matter. The digestion in most species is brought about by flagellates that live in the intestines and secrete cellulase. The species that utilize organic residues do so very completely, and markedly hasten the decomposition processes.

Beetles (Coleoptera)

The Coleoptera constitute a great variety of insects that live in and on the soil as larvae and adults (Kevan, 1962; Raw, 1967). A large percentage of the species are predatory on small animals but others feed on vegetable matter, fungi, algae, wood, carrion, manure, etc. In fact, the variety and numbers of beetles are so large, and their habits so diverse, that there is scarcely any natural form of organic matter that is not attacked by one or more kinds of beetles. Some species spend most of their life in litter, whereas others may burrow into the soil to a depth of several inches, carrying with them dung and other forms of organic matter. Because of their predatory habits one type of beetle may become so numerous and active that it can markedly decrease the population of other animals, both arthropods and non-arthropods. This predation may or may not have an overall beneficial effect on crop production, depending on the species involved.

Some beetles, such as the "May-beetle", lay their eggs at a depth of several inches in the soil and require several months for passage through the larval stage and eventual emergence of the adults at the surface. The large numbers that emerge at the same time might not seem to indicate such a slow transformation through the larval stage, but such is the case.

The extreme diversity and uniqueness of some of the beetles is illustrated by *Lomechusa strumosa*, a small subterranean staphylinid that lives in the nests of ants. According to Kevan, "eggs are not laid by this species, but young larvae are deposited directly on to the eggs of the ant. Soon after their emergence these young larvae lose any resemblance to staphylinid grubs and mimic the appearance and attitudes of ant maggots. In spite of the fact that the beetle grubs devour large numbers of their hosts' brood, the ants, when danger threatens, rescue their 'guests' before their own young! Not only this, but they place the intruders upon their own brood and feed both them and the adult beetles – which are quite capable of feeding themselves – from their own mouths! "

Larvae of flies (Diptera)

Numerous species of Diptera in the larval form, and a very few in the adult stage, are commonly found in the soil and in litter on the soil (Kevan, 1962; Raw, 1967). Most of them require a moist environment. Only a few are able to burrow into the soil but are confined to any natural openings that may be present. The few adults that do not leave the soil are for the most part wingless forms.

The foods used by the larvae, or maggots, include living and decaying vegetable matter, fungi, wood, feces, carrion, insect eggs, etc. Some larvae feed throughout most of the year on plant roots. Other species are predacious on other insects, earthworms, slugs, snails, etc. Like beetles, the species of Diptera are so numerous and varied that one or more will use almost any form of organic matter as a food source. Their main effect on soil fertility is the speeding up of degradative processes that lead to humus formation and release of nutrients from the digested materials.

Woodlice (Isopoda)

Woodlice are terrestrial representatives of predominantly marine and freshwater organisms. They prefer a saturated atmosphere and hence are largely confined to moist, dark habitats. It is their susceptibility to desiccation that largely determines the distribution of the species. Their food consists chiefly of decaying organic matter in the forms of vegetable matter, leaves and woodland litter. They are of minor importance in arable soils.

Ants (Hymenoptera)

Ants are a comparatively minor contributor to soil formation and organic matter decomposition. The common ants of the temperate climates construct an extensive underground system of galleries that may extend several feet into the soil. They live as a colony and sometimes entertain aphids as guests in their nest. They feed largely on living and dead insects. Their chief role in soil formation lies in their transport of subsoil to the surface.

SOIL ANIMALS, HUMUS FORMATION AND CROP PRODUCTION

In this chapter frequent reference has been made to the roles that different types of soil fauna play in soil formation, profile modification, the mixing of organic with inorganic constituents, destruction of animal and vegetable matter, predation on other animals, and in the overall acceleration of humus formation. In many instances these effects are far from minor although until comparatively recently little attention was paid to them. As Kevan (1962) says, the study of soil zoology is still in its infancy. The problems are intricate, the soil organisms show an enormous diversity, and the physical difficulties in studying them are not inconsiderable. Even the life histories of some of the common members are not completely known. For more detailed consideration of this subject reference should be made to Kevan (1962, 1968) and to Burges and Raw (1967).

TABLE 4.I

NUMBERS OF FAUNA BENEATH ONE SQUARE METER OF EUROPEAN GRASSLAND (adapted from KEVAN, 1965)

Fauna	*Numbers*
Earthworms (Lumbricidae)	30–2,000
Potworms (Enchytraeidae)	200–20,000
Slugs and snails (Mollusca)	100–8,500
Millipedes and centipedes (Diplopoda and Chilopoda)	900–1,700
Woodlice (Isopoda)	100–400
Spiders (Araneida)	180–840
Beetles and larvae (Coleoptera)	500–1,000
Fly maggots (Diptera)	approx. 1,000
Ants (Hymenoptera)	200–500
Springtails (Collembola)	10,000–40,000
Mites (Acarina)	20,000–120,000
Nematodes (Nematoda)	1.8–120 million

One of the best ways to emphasize the importance of the soil animals is to show their numbers as in Table 4.I, taken from Kevan (1965) – see also Fig.4.1. As Kevan states, the upper limits indicated in Table 4.I are not maximal. In woodland soils, enchytraeids may number up to 270,000 or more per square meter, mites up to 400,000 and Collembola up to 200,000. In cultivated heathland, 800,000 arthropods per square meter have been observed. Kevan states that, exclusive of nematodes and Protozoa, the estimated number of animals may total over 1.5 million per square meter. Fluctuations of numbers of different kinds of animals with environmental conditions and with seasons are very great. More important than numbers, however, are figures for biomass and respiration (see Kevan, 1965; Burges and Raw, 1967).

Kevan (1965) concludes that "the soil fauna cannot be dismissed as unimportant. It is estimated by Nef, in fact, that soil animals require a quantity of nutrients approximately equal to that provided by the litter produced annually by the surface vegetation." Kevan (1968) considers that "soil animals play an indispensable, if limited, role in humus formation. Their chief contribution would seem to be indirect and to lie in the degree to which microbial activity is enhanced by fragmentation of plant residues. The mixture of organic with mineral matter and the translocation of microorganisms is also important."

REFERENCES

Barley, K.P., 1959a. *Aust. J. Agric.Res.*, 10: 171–178.

Barley, K.P., 1959b. *Aust. J. Agric. Res.*, 10: 179–185.

Barley, K.P., 1961. *Adv. Agron.*, 13: 249–268.

Brown, E.B., 1955. In: D.K.M. Kevan (Editor), *Soil Zoology*. Academic Press, New York, N.Y., pp. 256–268.

Burges, A. and Raw, F., 1967. *Soil Biology*. Academic Press, New York, N.Y., 532 pp.

Christie, J.R., 1959. *Plant Nematodes – Their Bionomics and Control.* Agric. Exp. Stn. Univ. of Florida, Gainesville, Fla., 255 pp.

Darwin, C., 1881. *The Formation of Vegetable Mould through the Action of Worms with Observations on Their Habits.* 326 pp.

Doeksen, J. and Van der Drift, J. (Editors), 1963. *Proceedings of Colloquium on Soil Fauna, Soil Microflora and Their Relationships.* North-Holland, Amsterdam, 453 pp.

Evans A.C., 1948. *Ann. Appl. Biol.*, 35: 1–13.

Evans, G.O., 1955. In: D.K.M. Kevan (Editor), *Soil Zoology*. Academic Press, New York, N.Y., pp. 55–61.

Fellers, C.R. and Allison, F.E., 1920. *Soil Sci.*, 9: 1–25.

Franz, H., 1950. *Bodenzoologie als Grundlage der Bodenpflege.* Akademie-Verlag, Berlin, pp. XII,316.

Gerard, B.M., 1963. In: J. Doeksen and J. van der Drift (Editors), *Soil Organisms.* North-Holland, Amsterdam, pp. 49–54.

Guild, W.J.M., 1948. *Ann. Appl. Biol.*, 35: 181–192.

Guild, W.J.M., 1951. *Scottish Agric.*, 30: 220–223.

Hale, W.G., 1967. In: A. Burges and F. Raw (Editors), *Soil Biology.* Academic Press, New York, N.Y., pp. 397–411.

Harris, W.V., 1955. In: D.K.M. Kevan (Editor), *Soil Zoology*. Academic Press, New York, N.Y. pp. 62–72.

Jacot, A.P., 1935. *Sci Mon.*, 40: 425–430.

Jones, F.G.W., 1959. In: *Plant Pathology – Problems and Progress 1908–1958.* pp. 395–411.

Keith, A., 1942. *Nature*, 149: 716–720.

Kevan, D.K.M., 1955. *Soil Zoology*. Academic Press, New York, N.Y., 512 pp. (© University of Nottingham, Nottingham.)

Kevan, D.K.M., 1962. *Soil Animals*. Philosophical Library, New York, N.Y., 237 pp.

Kevan, D.K.M., 1965. In: K.F. Baker and W.C. Snyder (Editors), *Ecology of Soil-borne Plant Pathogens*. University of California Press, Berkeley, Calif., pp. 33–51.

Kevan, D.K.M., 1968. *Trans. Int. Congr. Soil. Sci., 9th, Adelaide, S.A., 1968*, II: 1–10.

Kleinig, C.R., 1966. *Aust. J. Agric Res.*, 17: 327–333.

Kühnelt, W., 1961. *Soil Biology with Special Reference to the Animal Kingdom*. (Translated by Norman Walker). Faber and Faber, London. 397 pp.

Mellanby, K., 1960. *Soils Fert.*, 23: 8–9.

Murphy, P.W., 1953. *J. Soil Sci.*, 4: 155–193.

Murphy, P.W., 1955. In: D.K.M. Kevan (Editor), *Soil Zoology*. Academic Press, New York. N.Y., pp. 99–124.

Newell, P.F., 1967. In: A. Burges and F. Raw (Editors), *Soil Biology*. Academic Press, New York, N.Y., pp. 413–433.

Nielsen, C.O., 1955. In: D.K.M. Kevan (Editor), *Soil Zoology*. Academic Press, New York, N.Y., pp. 202–214.

Nielsen, C.O., 1967. In: A. Burges and F. Raw (Editors), *Nematoda*. Academic Press, New York, N.Y., pp. 197–211.

Nielsen, G.A, and Hole, F.D., 1964. *Soil Sci. Soc. Am. Proc.*, 28: 426–430.

Nye, P.H., 1955. *J. Soil Sci.*, 6: 73–83.

O'Connor, F.B., 1967. In: A, Burges and F. Raw (Editors), *Soil Biology*. Academic Press, New York, N.Y., pp. 213–257.

Peters, B.G., 1955. In: D.K.M. Kevan (Editor), *Soil Zoology*. Academic Press, New York, N.Y., pp. 44–54.

Raw, F., 1967. In: A. Burges and F. Raw (Editors), *Soil Biology*. Academic Press, New York, N.Y., pp. 323–362.

Russell, E.W., 1961. *Soil Conditions and Plant Growth*. Longmans Green, London, 9th ed., XVI, 688 pp.

Satchell, J.E., 1955. In: D.K.M. Kevan (Editor), *Soil Zoology*. Academic Press, New York, N.Y., pp. 180–201.

Satchell, J.E., 1958. *Soils Fert.*, 21: 209–219.

Satchell, J.E., 1967. In: A. Burges and F. Raw (Editors), *Soil Biology*. Academic Press, New York, N.Y., pp. 259–322.

Singh, B.N., 1955. In: D.K.M. Kevan (Editor) *Soil Zoology*. Academic Press, New York, N.Y., pp. 403–411.

Stout, J.D. and Heal, O.W., 1967. In: A Burges and F. Raw (Editors), *Soil Biology*. Academic Press, New York, N.Y., pp. 149–195.

Thornton, H.G. and Crump, L.M., 1952. *Rep. Rothamsted (England) Exp. Stn.*, pp. 164–172.

Tischler, W., 1955. In: D.K.M. Kevan (Editor), *Soil Zoology*. Academic Press, New York, N.Y., pp. 215–230.

Wallwork, J.A., 1967. In: A. Burges and F. Raw (Editors), *Soil Biology*. Academic Press, New York, N.Y., pp. 363–395.

Walton, W.R., 1935. *U.S. Dep. Agric. Farmer's Bull.*, 1569: 1–14.

Chapter 5

PLANT ROOTS AND MICROORGANISMS

INTRODUCTION

The most important living organisms in soils are the higher plants. This is true whether they are considered from the standpoint of their direct value to man or from the standpoint of their contribution to soil formation and productivity. Higher plants are not only responsible for the synthesis of nearly all of the organic matter that reaches the soil but they are also responsible in a major way for the building up of a suitable soil crumb structure, and for increasing its supply of available nutrients. All of this is done in cooperation with the soil microflora and fauna; without higher plants all life on the earth would be reduced to near extinction. Presumably a few chlorophyll-containing algae and bacteria, and a few autotrophic bacteria could still live and synthesize organic compounds, but certainly their contributions to soil organic matter would be extremely small in comparison with what higher plants now contribute. There could be little, if any, higher animal life without higher plant life.

The cooperation of higher plants with living microorganisms, if it can be considered as such, occurs most intensively and strikingly in the root zone. The nature of this root-microorganism association, the reasons for it, and the effects on the higher plants are considered below.

RHIZOSPHERE

The area immediately surrounding a root, commonly referred to as the rhizosphere, is the seat of intense biological activity. Most kinds of microorganisms thrive in this region but usually it is the bacteria that are most responsive. Certain species are affected more than others which means that the composition of the microbial population in the rhizosphere may be markedly different from that of similar soil in which no plants are growing. So far as known, all plants have their rhizosphere population that may differ with kind and age of the plant, as well as with conditions under which the plants are grown.

The effect of the mass of microorganisms in contact with, or in extremely close proximity to, the plant roots and root hairs, varies widely. The products produced may be either beneficial or directly toxic (Börner, 1960; Woods, 1960). The organisms themselves may have little or no effect or they may be parasitic in or on the roots. At any one time a condition of biological equilibrium or balance between the various groups of organisms present is likely to prevail. This equilibrium is, however, rather unstable because a marked change in any one of the many factors involved in growth can be expected to have its effect on the population as a whole. Since all of this activity occurs in intimate contact with the root it is obvious that the effect on the plant may be marked.

Katznelson, Lochhead and associates have shown that there is not only a marked increase in numbers of microorganisms in the rhizosphere, but an increase in those that require amino acids for growth, and also an increase in the rapidly-growing organisms. This shift toward amino-acid-requiring bacteria was observed on roots that were only 2–3 days old. After that, the relations become more complicated because of the associative and antagonistic reactions among the microorganisms themselves. In addition to the competition for food, oxygen, and possibly growth factors, there are often inhibitory substances, such as antibiotics, that exert an effect (see Chapter 18).

In studies of the exudation of amino acids from the roots of tomato, subterranean clover, and phalaris, growing in nutrient solution, Rovira (1959) found that exudation was greater during the first two weeks of growth than during the following two-week period. Higher light intensities and temperatures usually increased exudation from tomatoes and subterranean clover. Calcium and degree of aeration had little effect.

In pure-culture inoculation experiments, made by Rovira (1963), it was found that *Azotobacter* did not colonize the roots of lucerne, maize, tomato, or wheat to any great extent. *Clostridium* and a facultative nitrogen-fixing bacillus were moderate colonizers. In mixed-culture, or unsterilized soils, where competition is likely to be very intense, one would expect even less success in attempts to influence the rhizosphere population by adding foreign organisms.

The microorganisms surrounding the roots are active in the breakdown of any crop residues or other energy sources, and in the overall humification process. Since the rhizosphere organisms are known to be more active than are those located elsewhere in the soil mass (Katznelson, 1960), it follows that this humification process in the rhizosphere is accelerated at least to the extent that the numbers are increased. Starkey (1931a) observed such a correlation.

NUMBERS AND KINDS OF MICROORGANISMS IN THE RHIZOSPHERE

Numerous workers (Starkey, 1929a,b,c, 1931a,b, 1938, 1958; Timonin, 1940; Lochhead, 1940, 1959; Katznelson et al., 1948; Clark, 1949; Rovira, 1956a,b, 1959; Papavizas and Davey, 1961; Rovira and Harris, 1961) have shown not only that large populations of bacteria, and other organisms are found at the root surface, but that the numbers show a very marked decline at distances of less than a millimeter from the root. The bacteria form a film or mantle around each root and root hair. They are not always uniformly distributed around the roots, but are often grouped in colonies located so close together that they function essentially as a film. Typical data obtained by Katznelson (1960), shown in Table 5.I, emphasize the magnitude of the rhizosphere effect. The data are

TABLE 5.I

RATIOS OF NUMBERS OF DIFFERENT TYPES AND GROUPS OF ORGANISMS IN RHIZOSPHERE SOIL TO NUMBERS IN CONTROL SOIL (R/S – from KATZNELSON, 1960)

Group	*Wheat*	*Mangels*
Total bacteria	21	120
Actinomycetes	–	23
Fungi	10	19
Protozoa	3	23
Algae	1	2
Nitrifying bacteria	1	1
Spore formers	2	–
Aerobic cellulose decomposers	6	3
Anaerobic cellulose decomposers	4	–
Gas-producing anaerobes	12	14
Anaerobes	2	46
Ammonifiers	50	167
Denitrifiers	90	230
Azotobacter	–	2

reported as ratios of numbers of microorganisms in the rhizosphere to numbers in the control soil.

The data in Table 5.I show a rhizosphere effect to various degrees for all of the groups of organisms except algae, nitrifying bacteria, spore formers and *Azotobacter*. A preferential stimulation was observed for the ammonifiers and denitrifiers. The 230-fold effect that occurred with the denitrifying organisms on mangel roots may be atypical, but the 120-fold effect noted for all bacteria is in harmony with what others have occasionally found. Such high values may be very temporary since they are dependent upon ideal environmental conditions in the root zone and excellent plant growth, and these conditions may change rapidly.

EFFECT OF KIND AND AGE OF PLANTS

The roots of essentially all garden and field crops are favorable for the development of large populations of nonsporulating, gram-negative rods but present information does not justify the listing of the plants in order of their bacterial populations (Katznelson et al., 1948). Even the results obtained for many kinds of plants of the same age, and grown under identical conditions, are not necessarily comparable. The stage of development of the various plants is necessarily different since they have different growth rates and do not all mature at the same time.

A rapid selective multiplication of the microflora on the seeds and roots of oats and tomatoes during germination and root development was observed by Rovira (1956a). This same observation has been made by many others working with other plants (Katznelson et al., 1948). The multiplication of bacteria is usually very rapid initially; later growth is dependent upon the plant species and metabolic activity of the higher plant (Starkey, 1929b; Timonin, 1940; Rovira, 1956a). After the death of the plant usually a rapid decline in bacterial numbers occurs (Starkey, 1929b; Katznelson et al., 1948). The density of the microbial population on roots seems to be dependent more on the metabolic activity of the crop under investigation than on soil treatment except as such treatment affects plant growth and health. After the death of a plant or of a single root, and decay has started, then the numbers of bacteria, actinomycetes and fungi may become very large, but this is not a true rhizosphere effect.

Rovira and McDougall (1967) give an excellent summary of our knowledge of the kinds of microorganisms that inhabit the rhizosphere, effect of age of plant, and the influence exerted on the various metabolic activities that they bring about or affect.

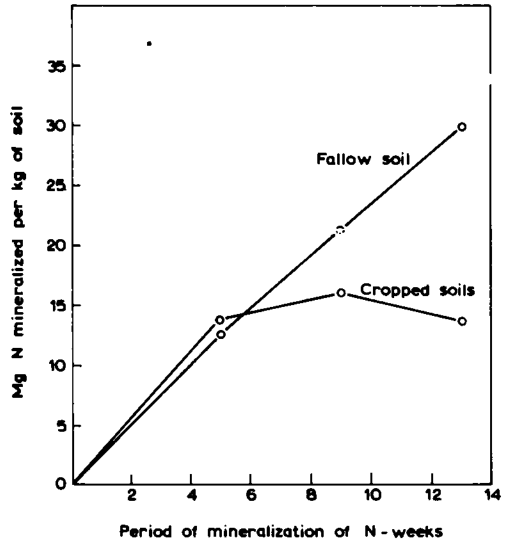

Fig.5.1. Mineralization of nitrogen in cropped and fallow soils after 5, 9, and 13 weeks. (From Goring and Clark, 1948.)

Fig.5.1, taken from the publication of Goring and Clark (1948), shows very strikingly the effect that plants and their associated rhizosphere bacteria have on mineral nitrogen in soil. In this experiment several kinds of plants were grown in pots for a period of 13 weeks, and other pots were left uncropped. At three intervals the mineralized nitrogen was determined in representative and similarly-treated cropped and uncropped soils. In the case of cropped soils this included mineral nitrogen in the soils plus the total nitrogen in the plants (tops plus roots). In all cases allowance was made for the nitrogen added in the fertilizer and seeds, or present in the soil initially. It will be noted that mineralization in the fallow soil continued at only a slightly decreasing rate until the end of the experiment. In the cropped soils maximum mineralization was usually observed at about the time of maximum vegetative growth. Thereafter there was a progressive disappearance of mineral nitrogen from the soil and an increase in bacterial numbers. The decrease in mineralization of nitrogen in the cropped soils was attributed to the increased uptake of nitrogen by the rhizosphere populations in these soils.

EXPLANATION OF THE RHIZOSPHERE EFFECT

Several possible explanations for the proliferation of microorganisms at or near the surface of roots have been suggested by various workers. These include the favorable reaction of near pH 6 that most roots tend to maintain during active growth regardless of the pH of the soil. Even though the microorganisms do not enter the root cells, they presumably might benefit from the root buffering effect. The root is constantly liberating carbon dioxide which might also help in the maintenance of a favorable reaction and in addition increase the solubilization of soil minerals (Gerretsen, 1948). Another suggestion is that the film of moisture on the root surface may offer an especially favorable environment for microorganisms. These three suggestions now appear to be of such minor importance in explaining the rhizosphere effect that they will not be considered further in the present discussion. It is the food supply derived from the roots that deserves the most attention and which will be considered in some detail, in the following pages.

Root exudates

It is now well established that roots of plants exude a large number of organic (and also mineral) substances and that it is this constant food source that is primarily responsible for the rhizosphere effect (Börner, 1960). Quantitative data on amounts of the various substances that are excreted from the roots are almost nonexistent, but the magnitude of the proliferation of microorganisms immediately surrounding the roots shows positively that the food supply furnished by the roots is substantial (Stille, 1959).

Rovira (1962, 1965a) summarized the information now available on the nature and source of the exudates of the various kinds of plants that have been investigated. The facts as he presented them are certainly impressive and leave no doubt as to why microorganisms find the rhizosphere such an ideal place for their development. These facts emphasize that growing plants are important contributors to the overall soil organic matter picture. This is true even though the total quantity of substances exuded may be small in comparison with the weight of the crop residues returned annually. The exudate contribution, because of its nature and constancy, and because of the tremendous biological response that it produces at the root surface, may be far more important than has generally been supposed. It certainly cannot be ignored in a broad consideration of soil organic matter and its functions.

The data assembled by Rovira (1965a) are presented here in Table 5.II–V. Reference

TABLE 5.II

SUBSTANCES DETECTED IN ROOF EXUDATES (from ROVIRA, 1965a)

Substance	*Plant*
Carbohydrates:	
Glucose	peas, wheat, soybean, barley, oats, mustard, white pine
Fructose	peas, oats, sorghum, mustard
Sucrose	bean
Xylose	sorghum, mustard, wheat, white pine
Maltose	mustard, bean
Rhamnose	wheat
Arabinose	white pine, wheat
Raffinose	white pine, wheat
Oligosaccharide	oats, wheat
Unidentified	sugar beet
Growth factors:	
Biotin	flax, rice, bean, clover, maize, peas, lucerne, phalaris, tomato, cotton
Thiamin	flax, rice, bean, clover, maize, peas, cotton
"M" factor	pine, peas, tomato
Pantothenate	clover, lucerne, phalaris, tomato
Niacin	clover, lucerne, phalaris, tomato
Choline	cotton
Inositol	cotton
Pyridoxine	cotton
p-Amino benzoic acid	cotton
n-Methyl nicotinic acid	radish
Organic acids:	
Tartaric	sorghum, mustard, wheat
Oxalic	sorghum, mustard, wheat
Citric	mustard, wheat
Malic	mustard, wheat
Acetic	wheat
Propionic	wheat
Butyric	wheat
Valeric	wheat
Succinic	wheat
Fumaric	wheat
Glycolic	wheat
Nucleotides, flavonones and enzymes:	
Flavonone	peas, wheat
Adenine	peas, wheat
Guanine	peas, wheat
Uridine and cytidine	peas, wheat
U.V.-absorbing compounds	peas, oats
Phosphatase	maize
Invertase	wheat, maize, peas
Amylase	wheat, maize, peas
Protease	wheat, maize, peas
Polygalacturonase	lucerne, clover

TABLE 5.II *(continued)*

Substance	*Plant*
Miscellaneous compounds:	
Auxins	pinto bean
Scopoletin	oats
Fluorescent substances	oats, peas, lucerne, banana
Hydrocyanic acid	flax
Glycosides	asparagus, oats
Saponins (glucosides)	lucerne
Organic phosphorus compounds	maize, pumpkin
γ-MnO_2-dissolving compound	oats, vetch
Bentonite colouring compound	red clover
Nodulation inhibitor	soybean
Azotobacter growth stimulator	barley, wheat

TABLE 5.III

AMINO ACIDS DETECTED IN ROOT EXUDATES BY SEVERAL INVESTIGATORS (from ROVIRA, 1965a)

Amino acid	*Sunflower*	*Oats*	*Maize*	*Peas*	*Peas*	*Rice*	*White clover*	*Perennial ryegrass*	*Wormwood*	*Tomato*	*Wheat*	*Wheat*	*Wheat*	*Wheat*	*Subterranean clover*	*Phalaris*	*Monterey pine*	*Flax*	*Cotton*
Leucine/isoleucine	*	*	*	*	*	–	*	*	*	–	*	–	*	*	*	*	*	–	*
Valine	*	*	*	*	–	–	*	*	*	–	–	*	*	*	*	*	*	–	–
γ-Aminobutyric acid	tr	*	–	*	–	–	–	–	–	–	–	*	*	*	*	*	*	*	–
Glutamine	*	*	*	*	*	–	–	–	–	–	*	*	*	*	*	*	*	–	–
α-alanine	*	*	*	*	*	–	*	*	*	*	*	*	*	*	*	*	*	*	–
Asparagine	*	*	*	*	*	*	–	–	–	–	*	*	*	*	*	*	*	–	–
Serine	tr	*	*	*	–	–	tr	tr	*	–	–	*	*	*	*	*	*	–	*
Glutamic acid	*	*	*	*	*	*	*	*	tr	*	–	*	*	*	*	*	*	*	–
Aspartic acid	*	*	*	*	*	*	*	*	*	*	–	–	*	*	*	*	*	*	*
Cystine/cysteine	–	*	–	–	*	*	–	–	–	*	–	*	–	*	*	*	–	–	*
Glycine	–	*	–	–	*	–	–	–	–	*	–	*	*	*	*	*	*	–	*
Phenylalanine	*	*	–	*	–	–	–	–	–	–	–	–	–	*	*	–	tr	–	*
Threonine	*	*	–	*	*	–	–	–	–	–	–	*	–	*	*	*	*	–	*
Tyrosine	–	*	–	*	–	*	–	–	–	*	–	–	*	–	–	–	–	–	*
Lysine	–	*	–	*	–	*	–	–	–	–	*	–	–	–	–	–	–	–	*
Proline	–	–	–	–	*	–	–	–	–	–	–	*	*	–	–	–	*	–	*
Methionine	–	–	–	*	–	*	–	–	–	–	–	–	*	*	*	*	*	–	–
Tryptophane	–	–	–	*	–	*	–	–	–	–	–	–	–	–	–	–	*	–	–
Homoserine	–	–	–	*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
β-alanine	–	–	–	–	–	–	–	–	–	–	–	–	–	*	–	–	*	–	–
Arginine	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	*

– = absent or not recorded; * = present.

TABLE 5.IV

NEMATODE-STIMULATING FACTORS FROM ROOT EXUDATES (from ROVIRA, 1965a)

Factor	*Plant*
Potato eelworm cyst hatching factor	potato and other Solanaceae
Beet eelworm cyst hatching factor	beet, rape
Cabbage eelworm cyst hatching factor	black mustard
Hop eelworm cyst hatching factor	hop
Heterodera spp. attractors	potato, cress, tomato
Meloidogyne spp. attractors	tomato

TABLE 5.V

FACTORS IN ROOT EXUDATES AFFECTING FUNGI (from ROVIRA, 1965a)

Factor	*Plant*	*Fungus affected*
Mycelium-growth stimulators	radish, lettuce	*Pellicularia filamentosa*
Mycelium-growth stimulators	strawberry	*Rhizoctonia* sp.
Mycelium-growth inhibitor	oats	*Byssochlamys nivea*
Mycelium-growth inhibitor	potato, *Datura* spp.	*Spongospora subterranea*
Mycelium-growth inhibitor	tomato	*Colletotrichum atramentarium*
Mycelium-growth inhibitor	turnip	*Pythium mamillatum*
Mycelium-growth inhibitor	peas	*Aphanomyces eutiches*
Mycelium-growth inhibitor	*Allium* spp.	*Sclerotium cepivorum*
Mycelium-growth inhibitor	tomato, radish, lettuce	*Fusarium* spp.
Mycelium-growth inhibitor	beans	*Fusarium solani* f. *phaseoli*
Mycelium-growth inhibitor	banana	*Fusarium oxysporum* f. *cubense*
Spore-germination inhibitors	banana	*Fusarium oxysporum* f. *cubense*
Spore-germination inhibitors	peas	*Fusarium oxysporum* f. *pisi*
Zoospore attractors	strawberry	*Phytophthora fragariae*
Zoospore attractors	peas	*Phytophthora erythroseptica*
Zoospore attractors	Solonaceae	*Phytophthora parasitica*
Zoospore attractors	avocado	*Phytophthora cinnamomi*
Pathogenicity stimulator	peas	*Fusarium oxysporum* f. *pisi*
Microsclerotia-germination stimulators	tomato, wheat	*Verticillium albo-atrum*

should be made to his article for the original sources of the information presented here.

The more common sugars, as shown in Table 5.II, are found in the exudates. Katznelson et al. (1954, 1955) observed marked excretion of sugars, but only when the plants were brought to the wilting point.

Most of the amino acids (Table 5.III) and many unidentified amino compounds have been detected in root exudates but not in all plants examined. These findings harmonize well with the observations of Lochhead and associates, as well as with those of Katznelson, that many of the rhizosphere bacteria have special amino acid requirements, and the higher plants can supply them.

Data on vitamins or growth factors (Table 5.II) are rather limited, partly because of the experimental difficulties in collection and assay. The work of Rovira and Harris

(1961) indicates that vitamin excretion is fairly common, even if in limited amounts. Some rhizosphere bacteria require them from outside sources, just as they do amino acids, and apparently roots are helping materially in meeting these needs and thereby increasing microbial activities in the rhizosphere.

Table 5.II shows that at least a few plants exude small amounts of organic acids. Further studies are needed to demonstrate if such exudation is common and appreciable.

The exudation of nucleotides, flavonones and enzymes from roots has also been demonstrated (Table 5.II) but the evidence for such exudation is still very limited.

The available evidence on the exudation of miscellaneous and unidentified compounds is also shown in Table 5.II. Nematode-stimulating and hatching factors (Table 5.IV) are also frequently present in root exudates. Likewise, factors that affect the growth of fungi, shown in Table 5.V, are commonly present. These data in Table 5.II–V, assembled by Rovira, suggest that most of the simple organic compounds formed in plants are able at times to escape from roots in at least detectable amounts.

Radioactive techniques are now being applied to studies of exudates with excellent results. McDougall (1968), for example, grew wheat seedlings under aseptic conditions in the presence of $^{14}CO_2$ and under satisfactory conditions for photosynthesis. After approximately one hour, labeled sucrose appeared in the roots. After 12 hours 50% of the ^{14}C in the soluble fraction was still in the sucrose, and the remainder of the radioactive carbon was present as glucose, fructose, raffinose, glutamine, glutamic acid, aspartic acid and unidentified compounds. Within three to four hours after the start of the experiment ^{14}C-compounds appeared in the root exudates. Exudation occurred mainly from the basal portions of the roots even though the root tip contained higher concentrations of radioactive carbon compounds. Root damage also favored increased exudation.

It has long been known that most or all of the important major and minor mineral nutrients may escape in appreciable amounts from the roots under many conditions of plant growth and climatic changes. As much as 5–25% of some elements or substances may under extreme conditions escape to the soil, and under normal conditions at least trace amounts may leave the root more or less regularly. This includes ammonia, nitrites and nitrates (Wilson, 1943).

In the evaluation of these results on exudates, it should be emphasized that the experimental difficulties in this type of work are great. The plants must be grown aseptically and usually in solution cultures, which is of course an abnormal environment. If sterilized soils are used then toxicity may be encountered. Even if such toxicity is avoided there is the problem of adsorption; practically all of the substances to be tested for, except possibly the sugars, are almost completely and quickly adsorbed by soils and held so tenaciously as to make extraction impossible. Since aseptic conditions are required it is also the usual practice to limit studies to the seedling stage. What we need are quantitative data collected under controlled growth conditions over the lifetime of numerous representative plant species. This ideal goal is not a practical one at the present time, but until information is available we cannot be too dogmatic about the amount of material released in root exudates.

Rovira's conclusion seems to sum up the present status very well. He states that "the importance of root exudates in influencing soil microorganisms, both pathogens and saprophytes, has now been demonstrated for many plants. There is little doubt that during the early stages of plant growth, root exudation is the major factor contributing to the rhizosphere effect whereby some microorganisms are stimulated while others are suppressed. Although the importance of this rhizosphere population in plant growth has yet to be established, the control which plants exert over the population by means of root exudates is important."

Sloughed-off root hairs and other tissues

The absorption of materials from the soil by roots takes place through the layer of young epidermal cells located at or near the root tip and extending backward for varying distances. The uptake of nutrients is greatly increased by the development of root hairs. The number of these is often as great as 200–400/mm^2 at or near the tip of the young growing roots. The factors that determine the numbers formed on any given plant species include most of the ordinary environmental conditions, such as nutrient supply, solution concentration, pH, available water, temperature, toxic substances and obstructions. The age of the plant and its growth rate are also very important. As the root tissues age they become modified by the deposition of cutin, formation of cork cells, and loss of root hairs. When this occurs most or all of their absorbing power is lost.

Root hairs are not roots but are merely single elongated epidermal cells that serve to increase greatly the absorbing surface. They commonly range in length from a fraction of a millimeter to 5 or perhaps 10 mm, depending on the medium in which they are grown and the general environmental conditions. The usual tendency is for a portion of the epidermal cells to form long tube-like structures having a diameter of about 10 μ and a cell wall thickness of 1 μ or less. As the root hair pushes through soil it is likely to assume almost any shape, or to be greatly retarded in growth as a result of the obstructions encountered.

The rate of elongation of a root hair under excellent growth conditions is likely to be 1–4 mm per 24-h day, or at an average rate of perhaps 2 mm. Only about 1–4 days are required for the completion of the growth of a root hair on most of our common cultivated crops (see also Chapter 16).

The length of time that root hairs continue to function varies widely with plant species and with moisture conditions in the soil. Usually they live for only a few days or weeks under the best conditions, but when the soil becomes too dry the root hairs of most plant species may disappear in a very short time. When soil conditions again become favorable a new set of root hairs is likely to develop but not from the same epidermal cells. Anything that seriously disturbs the condition of the plant, such as grazing or a radical change in light conditions, will also have a marked effect on root hair longevity.

Root-hair walls consist chiefly of cellulose and calcium pectate in layers continuous with corresponding layers in the epidermal hair-forming cell. There is also evidence for the presence of small amounts of fatty materials in both the epidermal and root-hair cell walls. Much work has been done on the mechanism of root-hair development and growth but conflicting opinions still prevail. It is established, however, that both calcium and auxins play important roles in the process.

Since root hairs are very fragile and easily affected by changes in soil conditions, and in the physiological status of the plant, it follows that an unknown part of the rhizosphere effect can be attributed to the food made available to the rhizosphere bacteria whenever root hairs die. This food source may be a minor one in comparison with root exudates, but it is quite important at times.

Root tissues other than root hairs are also being sloughed off in appreciable amounts at intervals and serve as energy sources for the micropopulation. This loss of tissues is usually small during the early stages of the normal growth of seedling plants, but as maturity approaches the amount of released tissue may be comparatively large. Even during the active growth period any sudden disturbance of plant growth can cause the death of root tissues. Such disturbance may be brought about by severe plant shading, removal of a portion of the tops by clipping or grazing, deficient or excess moisture, and other sudden changes in growth conditions. The effect of such factors on the rhizosphere population may be marked at times; however, an abundance of microorganisms may be found around plant roots at times when the plants are growing at a maximum rate.

A few attempts to measure the amount of organic debris added to soils via sloughed-off root cells have been made, but the difficulty in removal of all of the living root tissues from the soil leads to high values. Furthermore, sloughed-off material is undergoing decomposition at all times and hence measurements made at any one time do not record the total amount of such material released. This would make any measured values too low and tend to offset high values due to incomplete removal of living tissues. The continual decomposition of root substances would add microbial carbon to the soil but the larger portion of the carbon of the decomposing root tissues would be released to the air as carbon dioxide. Bearing in mind these difficulties of measurement it is of interest to note that Shamoot et al. (1968), using carbon-14, measured the deposition of organic debris in soils in which several kinds of plants were grown from the seedling stage to near maturity. They reported that the magnitudes of rhizo-deposition were directly related to the extent of root growth and ranged from 25 to 49 g residual organic debris for each 100 g of harvested roots. These authors were of the opinion that "the total quantities of deposition were much greater than those which were measured at the time of harvest" since much of the released material had been decomposed prior to harvest.

A special case of loss of root tissues occurs on legumes when they lose their nodules. The writer has, for example, observed that nodules may be abundant on some annual legumes, such as soybeans, during the early summer months when moisture is abundant, but if a dry period follows, nodules may disappear almost completely. This may occur even though the plants are still young and capable of growing rapidly. Nodules may again form in abundance on such plants within a period of a few days following heavy rains.

EFFECTS OF RHIZOSPHERE MICROORGANISMS ON PLANTS

The mantle of rhizosphere microorganisms that surrounds plant roots exerts a profound effect on the growth of the plant, but present data are inadequate to permit adequate evaluation of these effects (Rovira and Bowen, 1960; Bowen and Rovira, 1961; Estermann and McLaren, 1961; Rovira, 1965b). It is known that they may be either beneficial or harmful, and the effect doubtless varies widely with plant species and with the environmental conditions prevailing in the root zone. These effects are derived both from products released from the microbial cells, and from the decomposition products of the organic substances on which they live (Harley, 1948; Clark, 1949; Schmidt, 1951; Stallings, 1954; Starkey, 1958; Lochhead, 1959; Börner, 1960; Rovira, 1962; McCalla and Haskins, 1964). In addition, there are the possible major effects resulting from increased availability of nutrients as a result of biological action in the rhizosphere (Gerretsen, 1948; Clark, 1949; Thornton, 1956; Starkey, 1958). Conversely, there is the possibility of increased nutrient deficiencies for the higher plant resulting from competition for the nutrients by the microflora. Under rhizosphere conditions, where biological competition proceeds at a near maximum rate among the saprophytic organisms present, the effect on any parasitic organisms present is likely to be great, and highly beneficial to the higher plant. Ayers and Papavizas (1963), for example, observed that bacteria from the rhizosphere of beans produced an antibiotic that was selectively active against several plant-pathogenic and saprophytic fungi but was relatively inactive against bacteria. The data suggested that these bacteria by means of the antibiotic play a role in the suppression of root-infecting fungi in soil. This subject is discussed at some length in Chapter 19.

It is the intimate association of the rhizosphere population with the epidermal root cells and with the root hairs derived from them, that emphasizes their importance in plant growth. It is now well established that many simple organic and inorganic substances, such as antibiotics or growth-stimulating substances that are produced by microorganisms may move directly into the plant under many conditions and have a greater effect than if produced at some distance in the soil. In the latter case much or all of the synthesized substance may be adsorbed by the soil, or be decomposed, but in the rhizosphere such soil adsorption may be bypassed.

Present information indicates that the concentrations of the microbially-synthesized substances are low and hence are more likely to be stimulating to plant growth than to be toxic. If so, this is indeed fortunate. Such a finding would not necessarily mean that one species of a microorganism in the rhizosphere might not have a major effect on other species; the effect might be exerted through the food supply, growth rate, effect on pH, oxygen depletion, and numerous other channels that regulate or determine the growth of microorganisms. It is likely, for example, that a rapidly-growing saprophytic microorganism might so dominate the rhizosphere that a slower-growing parasite would have little opportunity to get started. The same situation may also occur among saprophytes, thus accounting for the fact that the rhizosphere population differs from that of the soil mass.

RESIDUAL EFFECTS OF THE RHIZOSPHERE POPULATION

Quantitative data on the persistence of the rhizosphere bacteria in soil after the death of the higher plants are not available. We know, however, on the basis of general observations that this flora decreases rather rapidly when this occurs. Since these microorganisms are dependent upon host plants for most of their energy supply, it is obvious that they will disappear rapidly when it is no longer available unless they are able to live on the decaying plant roots. Some of the organisms can do this but many cannot. Even those that can live saprophytically on the root residues will die, or go into a resting stage, within a short time because the supply of available carbohydrate is then very limited. Those that can attack cellulose, hemicellulose and lignin can continue growth at a constantly decreasing rate.

MYCORRHIZAL ASSOCIATIONS

Another kind of root-microorganism association that involves many kinds of plants is that in which certain fungi live in or on the roots. These fungi, mentioned in Chapter 3, are commonly called mycorrhizal fungi, and are not true rhizosphere organisms in the sense that this term is usually used. The fungi are not merely loosely associated with the plant roots as are the true rhizosphere microflora, but are so closely and permanently attached to the roots that they function as essentially a part of the root system (Schmidt, 1947; Harley, 1948, 1959; Wilde, 1954; Garrett, 1960; Hacskaylo, 1967).

Mycorrhizal fungi are divided into two groups, namely endotrophic and ectotrophic, depending on whether they live largely inside or outside the plant root cells. These mycorrhizal fungi, unlike root-rot fungi, usually do not injure the host plant when the plants are growing under favorable conditions, but live in a more or less symbiotic relationship with it. They live chiefly or wholly on the carbohydrates synthesized by the higher plants.

Most studies of mycorrhizae have dealt with those found on forest trees but they commonly occur on many other plants including shrubs, fruit trees, coffee, legumes, grasses and many cultivated crops. Wild plants and fruit trees are more likely to carry mycorrhizal fungi than are cultivated plants. They are so common on nearly all trees in natural forests that they can be considered as normal structures. Some plants form mycorrhizae with several species of fungi, whereas others are more specific. Some fungi can also attack more than one plant species, and often a single tree carries mycorrhizae produced by several fungal species. Present information indicates that there are all gradations among fungi with respect to their ability to attack plant roots. Some merely live in the soil saprophytically, others form mycorrhiza, and others attack and destroy the root (root-rot fungi).

The formation of mycorrhizae is favored by an abundance of organic matter, adequate but not excess moisture, and by good aeration. A moderate supply of nutrients seems to be more favorable than a very abundant supply. Mycorrhizae also need an abundant supply of simple carbohydrates, and hence their development is likely to be more vigorous on a plant that is actively photosynthesizing but which has a somewhat limited supply of available nitrogen. Such a plant would of course have a wide carbon–nitrogen ratio. Since abundant organic matter, such as forest litter, favors the development of mycorrhizae it is obvious that in the absence of a host plant, and possibly even in its presence, the ectotrophic fungus can utilize some of this energy source. Most of these fungi do not attack cellulose but it is entirely possible that they may utilize some of the energy supply released from the litter by other organisms. The mycorrhizae which replace or substitute for root hairs have the ability to supply their mineral needs, and those of the host, directly from the soil if the soil has an adequate supply available. The efficiency in nutrient uptake, especially of phosphorus, by the mycorrhizal system is usually much greater than by the nonmycorrhizal root system.

Endotrophic mycorrhizae are more closely associated with the host plant than are the ectotrophic organisms. These fungi do not form a mantle around the rootlets but penetrate into the cells and ramify through the root tissues, but usually without killing them. Little or none of the fungus is usually visible on the outside of the root. In some plants, such as the orchids, the seeds are infected with fungus hyphae and hence the microorganism is present in the plant during its entire life.

Endotrophic mycorrhizae are more common than are the ectotrophic but are not so well understood. This is partly because of the difficulty in growing them and also because they live inside the plant tissues. They are easily confused with nonmycorrhizal or root-rot fungi that may also be present. Endotrophic fungi are usually beneficial but not always, probably because they may under some conditions weaken the host plant and thereby increase the chances of infection by pathogenic organisms.

In his discussion of endotrophic mycorrhizae, Hacskaylo states that normally unless a specific fungus penetrates the orchid embryo, seed germination does not occur. It is of interest to know that some of these same fungi are serious pathogens on other hosts. Fig.5.2, taken from Hacskaylo's article, shows the appearance of endotrophic mycorrhizae of red maple. In this case the invaded roots are beaded as a result of periods of arrested growth followed by periods of active growth.

In the formation of ectotrophic mycorrhizae, the fungus hyphae enter the plant rootlet and envelop the entire root tip. Probably as a result of growth-regulatory compounds secreted by the fungus, the root undergoes marked changes in morphology without the development of root hairs. The root commonly remains short and may be branched, as shown in Fig.5.3, reproduced from Hacskaylo. Growth of the fungus is limited to the intercellular region of the cortex, and the normal metabolism of the root cells and fungus are not appreciably affected.

The status of our knowledge of the effects of mycorrhizae on tree growth was summarized by Levisohn (1958). He concluded that "the results of modern researches do, on the whole, agree that under conditions approximating to natural environments, mycorrhizal associations are not parasitic. Much circumstantial evidence has been advanced in support of their beneficial tendency, but only relatively few critical experiments have yielded incontrovertible proof of their stimulating effects on tree growth." It is often difficult to know whether vigorous growth is the result of mycorrhizal infection, or whether the fungi develop good mycorrhizae because of good tree growth.

Extensive studies by Wilde (1954) at Wisconsin with several species of coniferous and deciduous trees led him to the conclusion that mycorrhizal fungi are essential for the growth of forest trees. No evidence of parasitism was observed. In grassland soils these fungi are absent and trees grow there only if they are inoculated, or if nursery seedlings that invariably carry symbiotic organisms are used. The fungi persist in forest soils long after the forest no longer exists; radical changes of environmental conditions are required for extermination of the symbionts. He states that the fungi exert their beneficial effects

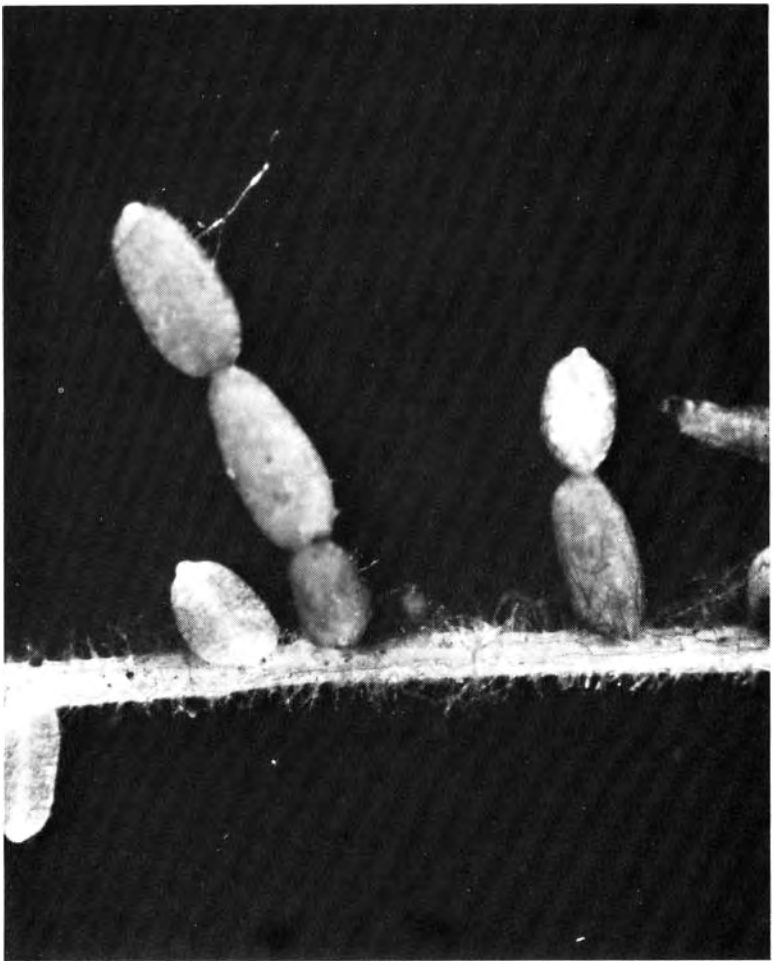

Fig.5.2. Endotrophic mycorrhizae of red maple. (From Hacskaylo, 1967.)

Fig.5.3. Ectotrophic mycorrhizae of Virginia pine. (From Hacskaylo, 1967.)

chiefly through their ability to increase the availability of nitrogen, phosphorus and other nutrients. He made the following very surprising statements: "Seedlings raised in forest soils continued to grow satisfactorily in prairie soils even though their root systems lacked mycorrhizal short roots or internal mycelia. This indicated that development of ectotrophic or endotrophic mycorrhizae in trees is only an incidental detail of a broader relationship of the *rhizospheric symbiosis.* The latter can be materialized through internal as well as external contact of root hairs with fungus mycelia, permitting the diffusion of soluble carbohydrates and nutrients. The intercellular and intracellular penetration of mycelia appears to be determined by the state of soil fertility, nature of the symbiont, and ability of roots to place a barrier against the invading fungus."

Hacskaylo (1967) is also very certain as to the benefits, or even essentiality, of mycorrhizae for tree growth when he says that "without mycorrhizae, many plants, including our most important timber species, could not survive in the dynamic, fiercely competitive biological communities that abound in natural soil habitats". A few other workers have been less certain of the essentiality of these organisms but this difference of opinion is to be expected, considering the wide variations encountered in dealing with many different fungi and host plants growing under a wide variety of environmental conditions.

Hacskaylo states further that "attempts to establish trees that normally possess ectotrophic mycorrhizae in some of those areas (where the fungi were absent) have failed time and time again. Some dramatic results have been recorded from introduction of mycorrhizal fungi in Australia, parts of Africa, the Russian Steppes, the Caribbean Islands, and in our own midwestern prairies ...... As mycorrhizal fungi became established on the root systems and the seedlings outplanted, rapid growth responses were very often apparent." One example that he cited was the attempt to establish pines in Puerto Rico. After 3 years uninoculated slash pine seedlings were less than 12 inches in height whereas inoculated plants reached heights of up to 8 ft. One strain of inoculated pine now often grows 10 ft. in one year.

There have been some claims to the effect that mycorrhizal fungi in association with plants are able to fix nitrogen but there is no proof, or even strong indication, that these organisms possess this ability. They do, however, increase the uptake of phosphorus and other elements and may also decrease the chance of infection by pathogenic organisms, perhaps through production of antibiotics (Santoro and Casida, 1962). Much of our knowledge of the role of mycorrhizal fungi, as already stated, is based on work done with trees; we are much in need of similar studies with cultivated crops. This subject is discussed further in Chapter 28.

REFERENCES

Ayers, W.A. and Papavizas, G.C., 1963. *Appl. Microbiol.*, 11: 533–538.

Börner, H., 1960. *Bot. Rev.*, 26: 393–424.

Bowen, G.D. and Rovira, A.D., 1961. *Plant Soil*, 15: 166–188.

Clark, F., 1949. *Adv. Agron.*, 1: 242:288.

Estermann, E.F. and McLaren, A.D., 1961. *Plant Soil*, 15: 243–260.

Garrett, S.D., 1960. *Biology of Root-infecting Fungi.* Cambridge University Press, London, XIX and 293 pp.

Gerretsen, F.C., 1948. *Plant Soil*, 1: 51–81.

Goring, C.A.I. and Clark, F., 1948. *Soil Sci. Soc. Am. Proc.*, 13: 261–266.

Hacskaylo, E., 1967. *Agric. Sci. Rev.*, 5: 13–20.

Harley, J.L., 1948. *Biol. Rev.*, 23: 127–158.

Harley, J.L., 1959. *The Biology of Mycorrhiza.* Interscience, New York, N.Y., 233 pp.

Katznelson, H., 1960. In: D. Parkinson and J.S. Waid (Editors), *The Ecology of Soil Fungi.* Liverpool University Press, Liverpool, pp. 192–201.

Katznelson, H., Lochhead, A.G. and Timonin, M.I., 1948. *Bot. Rev.*, 14: 543–587.

Katznelson, H., Rouatt, J.W. and Payne, T.M.B., 1954. *Nature*, 174: 1110–1111.

Katznelson, H., Rouatt, J.W. and Payne, T.M.B., 1955. *Plant Soil*, 7: 35–48.

Levisohn, I., 1958. *Soils Fert.*, 21: 73–82.

Lochhead, A.G., 1940. *Can. J. Res.*, 18: 42–53.

Lochhead, A.G., 1959. In: *Plant Pathology–Problems and Progress 1908–1956.* University of Wisconsin Press, Madison, Wisc., pp. 327–338.

McCalla, T.M. and Haskins, F.A., 1964. *Bacteriol. Rev.*, 28: 181–207.

McDougall, B.M., 1968. *Int. Congr. Soil. Sci., 9th, Adelaide, S.A., 1968, Trans.*, III: 647–655.

Papavizas, G.C. and Davey, C.B., 1961. *Plant Soil*, 14: 215–236.

Rovira, A.D., 1956a. *Plant Soil*, 7: 209–217.

Rovira, A.D., 1956b, *Plant Soil*, 7: 178–194.

Rovira, A.D., 1959. *Plant Soil*, 11: 53–64.

Rovira, A.D., 1962. *Soils Fert.*, 25: 167–172.

Rovira, A.D., 1963. *Plant Soil*, 19: 304–314.

Rovira, A.D., 1965a. In: K.F. Baker and W.C. Snyder (Editors), *Ecology of Soil-borne Pathogens.* University of California Press, Berkeley, Calif., pp. 170–186.

Rovira, A.D., 1965b. *Ann. Rev. Microbiol.*, 19: 241–266.

Rovira, A.D. and Bowen, G.D., 1960. *Nature*, 185: 260–261.

Rovira, A.D. and Harris, J.R., 1961. *Plant Soil*, 14: 199–214.

Rovira, A.D. and McDougall, B.M., 1967. In: A.D. McLaren and G.H. Peterson (Editors), *Soil Biochemistry.* Marcel Dekker, New York, N.Y., pp. 417–463.

Santoro, T. and Casida, L.E., 1962. *Can. J. Microbiol.*, 8: 43–48.

Schmidt, E.L., 1947. *Soil Sci.*, 64: 459–468.

Schmidt, E.L., 1951. *Soil Sci.*, 71: 129–140.

Shamoot, S., McDonald, L. and Bartholomew, W.V., 1968. *Soil Sci. Soc. Am. Proc.*, 32: 817–820.

Stallings, J.H., 1954. *Bacteriol. Rev.*, 18: 131–146.

Starkey, R.L., 1929a. *Soil Sci.*, 27: 319–334.

Starkey, R.L., 1929b. *Soil Sci.*, 27: 355–378.

Starkey, R.L., 1929c. *Soil Sci.*, 27: 433, 444.

Starkey, R.L., 1931a. *Soil Sci.*, 32: 367–393.

Starkey, R.L., 1931b. *Soil Sci.*, 32: 395–404.

Starkey, R.L., 1938. *Soil Sci.*, 45: 207–249.

Starkey, R.L., 1958. *Bacteriol. Rev.*, 22: 154–172.

Stille, B., 1959. *Recent Adv. Bot.*, 1: 604–610

Thornton, H.G., 1956. *J. Sci.Food Agric.*, 7: 93–101.

Timonin, M.I., 1940. *Can. J. Res. C*, 18: 307–317.

Wilde, S.A., 1954. *Soil Sci.*, 78: 23–31.

Wilson, J.K., 1943. *N.Y. (Cornell) Agric. Exp. Stn., Mem.*, 253: 1–36.

Woods, F.W., 1960. *Bot. Rev.*, 26: 546–569.

FORMATION AND NATURE OF ORGANIC MATTER OF MINERAL SOILS

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Chapter 6

SOIL ORGANIC MATTER FORMATION

INTRODUCTION

The process of formation of soil organic matter or humus is primarily a biological one, in which nearly all of the flora and fauna living in or on the soil play a direct or indirect part. A few types of fast-growing bacteria and fungi are the dominant microorganisms initially. These organisms are dependent upon organic materials for their source of energy, and if such materials are abundant, the microorganisms are not slow in utilizing them. Initially a period of luxury consumption is likely to prevail during which time energy is released at rates beyond the needs of the decomposing organisms. There then follows a slow but steady attack on the less available residual products when essentially all of the microorganisms in soil, both slow and fast growers, are involved.

Soil organic matter formation is not, however, wholly a degradation process. The microorganisms that are so active in the decomposition of plant and animal residues are using a portion of these for the building of their own bodies which soon become a considerable portion of soil organic matter. This synthesized material contains the same elements as were in the source materials, but may differ markedly from them in respect to both physical and chemical characteristics, and in the proportion of the various elements present. In the following discussion the decomposition processes will be considered first, and the synthetic ones later, but this is merely for convenience. Actually the two processes occur simultaneously and factors that affect one are likely to affect the other but not always in the same manner. For example, a comparatively high temperature may bring about the maximum rate of decomposition but a minimum synthesis per unit of material, whereas a lower temperature may produce the reverse effect. At the present time there are no reliable data on the portion of soil humus that is residual plant and animal material, and the portion that is of microbial origin. Some investigators consider that the synthetic portion in older humus is at least as great as the residual portion and probably much greater (Bartholomew, 1965). The two fractions are so intermixed, and the time involved in humus formation so great, that there seems to be little chance for a quantitative estimation of the two fractions, but we know that the microbial portion is not small even if not recognizable as such.

SOURCES, NATURE AND COMPOSITION OF PLANT AND ANIMAL SUBSTANCES

Only two types of organisms, found on the earth, are able to synthesize organic matter from inorganic elements and simple compounds. These are autotrophic bacteria and chlorophyll-containing plants. In terms of the total quantities of organic substances formed, the autotrophic bacteria are of minor importance. The chief autotrophic bacteria are those that oxidize ammonia and nitrites, sulfur and its compounds, iron, hydrogen and carbon monoxide. Green plants are responsible for synthesizing most of the organic matter found on the earth's surface. By means of chlorophyll, the energy of sunlight is captured and stored in the myriad of compounds that go to make up green plants. The building blocks consist of carbon dioxide from the air, nitrogen in part from the air and in part from the soil, water, and various minerals from the soil. Animals must of course obtain their energy supply and most of their nutrients for tissue building from plants and plant products that they consume.

Weiss (1955) has presented some very interesting figures that show the magnitude of the products produced through photosynthesis. He states that it has been estimated that about 400 billion tons of sugar are formed annually by this process. Marine and fresh water algae account for 90% of this and land plants for the remainder. About 67.5% of the synthesis by land plants is done by forests and 24.5% by cultivated crops. Most of the primary products of photosynthesis are either rapidly converted into other products or are used as energy by the producing plants. He estimates that only 2% of the products of photosynthesis by land plants is consumed by all animals. This would presumably represent about a third of the products produced by cultivated crops; the remainder is utilized as fuel, fiber, structural material, and for soil organic matter maintenance, or is unutilized.

The organic materials that serve as precursors of soil humus may reach the soil in the forms of whole plants and animals; as fractions of the original plants and animals, such as starch, protein, cellulose; or as partially decomposed mixtures of the original plant materials, including the microorganisms that originally synthesized the organic matter or were involved in its decomposition. Stated another way, the humus sources include chiefly such materials as crop residues including plant roots, animal manures, green manures, artificial manures and composts, dead animals, organic fertilizers, and microorganisms. All of these materials are mixtures of many chemical substances; pure compounds seldom, if ever, are added to soils except by scientists for experimental purposes.

The most commonly mentioned and usually the best understood organic compounds that find their way into the soil and are subject to the normal decomposition processes are the following: (1) carbohydrates (sugars, starches, hemicelluloses, cellulosans, pectins, gums, mucilages, etc.); (2) proteins, amino acids, amines, etc.; (3) fats, oils, waxes, resins, etc.; (4) alcohols, aldehydes, ketones, etc.; (5) organic acids; (6) lignin; (7) compounds having cyclic or ring structures (phenols, tannins, hydrocarbons); (8) alkaloids and compounds with organic bases, such as pyridine and purine; and (9) miscellaneous substances that are important but present in very small amounts, such as antibiotics, auxins, vitamins, enzymes and pigments.

The inorganic constituents, usually present to the extent of 2–15%, may include any or all of the major and minor elements.

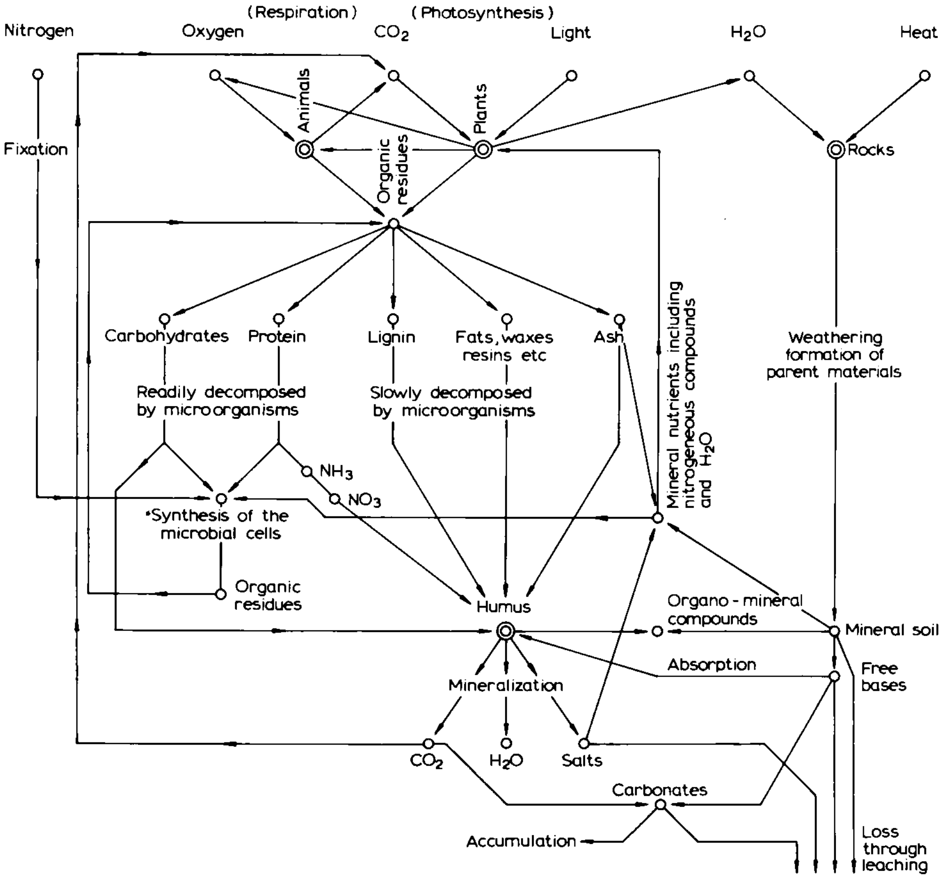

Fig.6.1. The relationships between the various processes concerned with synthesis and decomposition of humus in the soil. (From Nikiforoff, 1938.)

The main steps involved in the decomposition of organic substances, and in the synthesis and decomposition of humus in soils, are shown in Fig. 6.1, drawn by Nikiforoff (1938). The rate and extent of transformation of the various animal and plant substances into gaseous products and residual substances, including humus, minerals, water and synthesized materials, are dependent primarily on the conditions under which decay takes place, and on the microorganisms involved. These factors are discussed in the following pages.

The chemical composition of both plant and animal tissues is so complex that it is impossible to make a complete chemical analysis that shows quantitatively the exact compounds present. This is further complicated in plant analysis by the fact that marked changes occur at the different stages of plant growth. One must be satisfied in most cases by approximate analyses, such as those reported by Waksman and Tenney (1927a,b, 1928).

ORGANISMS INVOLVED IN DECAY

All heterotrophic microorganisms that live in soil or decaying organic matter are able to attack one or more organic substances. This statement is obvious since all living organisms must have an energy supply, and the only energy source available to heterotrophs is organic matter. Some of these microorganisms, including bacteria, fungi, and actinomycetes, can attack many types of compounds, whereas others are very selective in their feeding habits. In addition to the microflora, there is also a large and varied animal population, discussed in Chapter 4, that commonly plays a major role in the breakdown of organic residues that reach the soil. This animal population, including chiefly earthworms and many species of insects, speeds up the decomposition process by direct digestion of the organic debris; by comminution and mixing with soil; and by transportation from the surface into the soil where conditions are more favorable for rapid microbial attack.

When fresh plant materials are added to soil under favorable conditions for microbial growth an extremely rapid multiplication of microorganisms (bacteria, fungi and actinomycetes) takes place with the corresponding increase in carbon dioxide evolution, which is of course a direct measure of decomposition. This violent "biological explosion" is caused largely by fast-growing, spore-forming bacteria, designated by Winogradsky (1925) as zymogenous organisms. Other organisms, always present in soil but showing little fluctuation in numbers, constitute the autochthonous flora, according to Winogradsky. This classification of the microflora is simple and may seem logical but actually there is no sound scientific basis for it. Various workers since the time of Winogradsky have been unable to agree as to what types of bacteria belong to the two groups. Furthermore, seldom has anyone shown that the addition of readily decomposable substances to soils permanently changes the types of organisms present. The numbers of certain species are changed markedly of course but usually only temporarily. We now know that most or all of the so-called autochthonous bacterial species remain dormant because the conditions for growth are not satisfactory. If supplied with the proper energy sources, mineral nutrients and growth factors they are likely to grow fairly rapidly. The terminology, suggested by Winogradsky and never sharply defined, should be discarded.

There are many reasons why one organism may grow faster than another in a given soil environment. A few examples follow. One may be a heterotroph and another an autotroph; one may be able to utilize cellulose, whereas another cannot; one may be able to grow at a lower pH than another; one may be able to utilize nitrate as a hydrogen acceptor but another must have molecular oxygen. All of these and many other possible explanations may be grouped under about four headings: (1) Growth rate. The organism that can grow the fastest may dominate the substrate. (2) Growth medium. The nutrients and energy source needed by one organism are not the same as required by another. (3) Environmental conditions. Oxygen needs and pH, for example, are not the same for all organisms. (4) Inhibitory substances. The faster growing organisms may by means of antibiotics or inhibitory end products make conditions unfavorable for a competing organism. Of these four explanations, growth rate is especially important since the rapidly-growing organism can literally swamp, or overwhelm, the slow grower before it has a chance to initiate vegetative growth.

Exact information on the microorganisms responsible for the decomposition of plant and animal residues is not as extensive as might be expected, considering the amount of work that has been done on the subject. As Russell (1961) pointed out, this is due in large part to the tendency for most research workers to work with pure cultures of microorganisms, often cultured on chemically pure compounds. For example, in studies on cellulose decomposition it has been a common practice to use filter paper rather than natural cellulose that is commonly found associated with many other substances, such as hemicelluloses, lignin, proteins, gums, etc. The results obtained in such studies may bear little relation to what takes place in soil where natural residues are present and where there is a broad mixture of various species of bacteria, actinomycetes, fungi and usually fauna. Under such natural conditions usually there is at least one kind of organism that can attack every type of natural compound that is exposed to its enzyme system. Cellulose fibers in plant tissues may, for example, be protected by layers of hemicellulose, lignin, gums, waxes, etc. and not be decomposed by single species. In mixed culture this is not likely to be true for the encrusting materials are attacked separately. The oxidation of one compound by one type of organism exposes other substances to successive attacks by other groups of organisms. The result is to hasten markedly the overall rate of decomposition.

The environmental growth conditions may also be a very important factor that works in favor of the mixed cultures. For example, a bacterium such as *Cytophaga* may attack cellulose very readily in a neutral medium but not in an acid medium. However, in mixed cultures there may be an actinomycete or a fungus that can utilize cellulose very readily in such an acid medium. As has often been said, there is usually one or more species of microorganisms in most any soil that can decompose any natural constituent that is added to it although, admittedly, the attack may be slow initially either because few of the essential organisms are present, because growth conditions are unfavorable, or because it takes time to build up a suitable adaptive enzyme system.

FACTORS THAT AFFECT THE RATE AND EXTENT OF DECAY

Composition and particle size

Plant and animal residues that reach the soil contain a variety of compounds, and these vary widely in susceptibility to attack by microorganisms, as pointed out above. Simple carbohydrates and proteins are readily attacked whereas lignin and waxes are very resistant to decay. The quantities of each of these various substances and their arrangement in the plant tissues are likewise very important.

Fig.6.2, taken from Lockett (1937), shows the comparative rates of decay in soil of clover and rye plants of different stages of maturity. Their proximate composition is

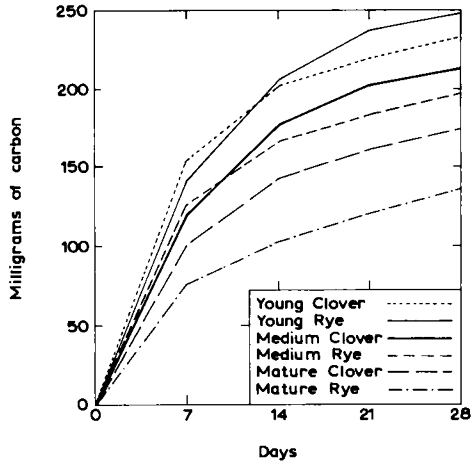

Fig.6.2. Course of evolution of carbon dioxide from rye and clover plants in soil containing 18% moisture. (From Lockett, 1937.)

given in Table 6.I. These data are typical of many that have been published. It will be noted from the figure that the rate of carbon dioxide evolution increased as the percentage of nitrogen in the plant products increased, and as the carbon–nitrogen ratio decreased. At the end of 28 days about 80% more carbon dioxide had been liberated from the more succulent materials than from the mature rye. It will also be noted from Table 6.I that the contents of hemicellulose, cellulose and lignin also increased, as they always do, as the plants became more mature. Therefore, both the contents of resistant materials and available nitrogen determine the rate of decomposition of plant materials in the process of humus formation.

The physical state of the plant materials is also an important factor. Succulent plant materials, such as a green manure crop, will decompose somewhat more rapidly than will

TABLE 6.I

PROXIMATE CHEMICAL COMPOSITION OF RYE AND CLOVER PLANTS AT DIFFERENT STAGES OF GROWTH (adapted from LOCKETT,1937)

Constituent	*Rye**			*Clover**		
	young	*medium*	*mature*	*young*	*medium*	*mature*
Hemicellulose	13.51	17.27	20.40	8.11	10.80	12.12
Cellulose	21.56	30.96	36.30	16.70	28.40	31.27
Lignin	3.98	7.20	11.33	3.82	5.68	8.36
Crude protein	10.55	6.97	2.37	11.67	8.70	4.91
Carbon–nitrogen ratios	24.9	37.5	110.8	22.5	30.2	53.5

*Values expressed in percentages.

the same materials after being subjected to thorough desiccation. Rewetting does not restore the plant materials to quite the same degree of hydration and succulence that existed previously. This effect is usually not marked and is more or less temporary.

Fineness of grinding is also an important factor in determining the rate of decay. Grinding exposes more surface for biological attack which is especially important for substances that are not readily penetrated by bacteria or by the hyphae of fungi. The grinding process commonly makes the plant material more susceptible to attack, but decay may be retarded by lack of oxygen. Finely-ground moist materials may pack together to such an extent that anaerobic conditions may develop in the center of the mass. Such a condition is unlikely to develop if these materials are mixed with medium-textured soils in moderate amounts. In compost piles and manure piles, however, oxygen deficiency is a common condition, and also often a desired condition if rapid and extensive oxidation is not desired. Certainly manure should be stored under anaerobic conditions.

The decomposition of plant materials may be accelerated by grinding, not only because more surface is exposed but also because a larger percentage of each plant constituent, such as cellulose, that may have been largely protected from biological attack by lignin, waxes or gums, is now exposed in major part to the enzymes of a myriad of organisms that may be present. Grinding insures that practically all plant substances are simultaneously exposed in part at least to any species that can attack them. If the material being exposed is largely of one kind, such as cellulose or protein, then grinding would probably be of less importance in determining rate of decay. Allison and Cover (1960), working with shortleaf pine sawdust, mixed with soil, observed that wood particles that barely passed through a 6-mesh sieve decomposed nearly as rapidly as did smaller particles. Larger wood particles decomposed more slowly. The rate of decomposition of more succulent materials, kept under favorable conditions for microbial growth, is not as markedly increased by grinding as might be expected. The fungus filaments penetrate these materials very readily so long as the oxygen supply is adequate.

A possible exception to some of the statements made above is emphasized by the work of Van Schreven (1964), who found that grinding may decrease the rate of decay of plant materials that have been oven-dried. This treatment increases the carbon–nitrogen ratio of the water-soluble organic fraction.

Microorganisms involved

The importance of the microbial population in the determination of the rate and extent of decay of organic residues is obvious since the microflora (and microfauna) are responsible for decay. This must be thought of in a quantitative as well as qualitative sense; there may be several kinds or species of organisms present that can attack a given substance but each has a different rate of, or capacity for, attack. A multitude of ecological factors will determine which kinds of organisms, or which species, do most of the work. A moderate change in ecological or environmental factors may disturb the microbial equilibrium thereby causing one species to be suppressed and another to be favored.

The various organisms that constitute the microflora are also far from inert with respect to the effect of one on the other. They are all directly or indirectly competitive with each other. They compete for organic and inorganic nutrients and for oxygen. The dominant species may also make the growth conditions less favorable for other organisms and this may be one reason why they remain dominant, at least for awhile. They make the conditions unsatisfactory for competitors not only by removing nutrients and oxygen but also through their secretions and excretions, and through the accumulation of their byproducts. Usually of course there is a succession of organisms, an organism that is dominant initially seldom remains dominant indefinitely. As the food supply diminishes, or the environment changes, another species is likely to take over. This succession of organisms commonly continues so long as there is a source of energy present that some organism can utilize, even if slowly.

The two most important factors that determine the type of organism that will grow best in the presence of a mixed and adequate organic food supply are pH and oxygen. In a near-neutral medium bacteria are usually very abundant, whereas in a rather acid medium the fungi are the chief agents of decay. If the oxygen supply becomes deficient, anaerobic and facultative anaerobic bacteria will replace the aerobic organisms if the medium is not too acid.

Available nutrients

All, or essentially all, of the elements needed for the growth of higher plants and animals are also needed by the microorganisms that decompose organic substances. Plants and animals, including the micro forms, have similar compositions and enzyme systems and hence require similar elements for tissue building and for catalytic purposes. This fact explains why outside additions of inorganic nutrients are seldom required for the nutrition of the microorganisms that are decomposing plant and animal tissues. About the only exceptions to this are where a comparatively pure substance, such as cellulose, is the organic substrate, or where the products of decomposition are being removed, as formed, by higher plants or other competing organisms. In such cases nitrogen is likely to be the most deficient element since the quantity needed for the synthesis of bacterial protein is comparatively large. Occasionally phosphorus is also inadequate but only rarely are any of the other 15 or so essential elements appreciably deficient when plant and animal products are being broken down biologically.

The importance of carbon–nitrogen ratio in plant materials has been much discussed over the years. If the ratio is narrower than about 25, and the plant material is not very fibrous, then decomposition by microorganisms may proceed at the maximum rate possible under the existing environmental conditions. Since plant materials usually contain about 40–45% carbon on a dry weight basis this means that plant substances that contain about 1.5–1.7% nitrogen do not need to be supplied additional nitrogen to insure rapid decomposition. However, if the plant material has a carbon–nitrogen ratio greater than about 25–30 (nitrogen content less than 1.2–1.5%) then decomposition may be slowed down initially unless a little nitrogen fertilizer is added to bring the carbon–nitrogen ratio below the critical range of near 25. The greatest nitrogen needs are usually manifest during the first few days of decomposition when the "biological explosion" occurs. After the peak of biological activity many of the organisms involved die, are in turn decomposed, and a portion of the nitrogen of their bodies is released for use by other microorganisms or higher plants (Allison and Klein, 1962). These facts regarding the carbon–nitrogen ratio apply to average plant materials that decompose readily; if much lignin is present, as in woods, then allowance must be made for the inert lignin and for the consequent slow rate of decay.

Moisture

Moisture is an important factor in the growth of microorganisms and in the rate of decay but the percentage present, above a certain minimum, is not critical (Bhaumik and Clark, 1948; Miller and Johnson, 1964). Indirectly, however, the percentage is often very important, especially in fine-textured soils, because the more moisture present the less oxygen available for microbial growth. In such soils the total air space present may differ little from that in a very sandy soil, but the smaller the soil particles the greater the capillarity and the greater the amount of water held by the soil against the pull of gravity. The air spaces between aggregates or soil particles are also much smaller in the clay than in the sandy soil and the free movement of water is greatly impeded. Likewise, the rate of diffusion of air into the soil and of carbon dioxide from the soil mass are also greatly reduced. If high moisture levels reduce biological activity the effect is therefore most often due not directly to too much moisture but indirectly to reduced oxygen supply. In fact, most soil organisms can grow very well in liquid media if adequate aeration is provided. If such cultures are undisturbed and unaerated it is common for many aerobic organisms to produce a mass of growth (film) at the surface and be largely free of growth at a depth of half an inch or even less.

The optimum moisture content of soils for the growth of aerobic bacteria is commonly expressed in terms of percentage of water-holding capacity of the soil. Because of textural differences, absolute amounts of water expressed in percentages of the dry weight of soil mean little. The optimum moisture content usually ranges between 50 and 100% of water-holding capacity.

Moisture content can better be expressed in units of tension, either as centimeters of water or in bar units, the bar being just slightly less than one atmosphere (76 cm Hg). In the studies of Bhaumik and Clark (1948) the peak rate of carbon dioxide production was observed at or near the 50 cm (0.05 bar) water tension for all soils, but the total production during a 15-day period was not markedly different over the range of 1–3,160 cm (3 bars) of water tension. Miller and Johnson (1964) observed peak production at 0.50–0.15 bar; the accumulated total over 14 days was about the same for tensions between 0 and 0.15 bar.

The provision of adequate moisture for masses of decaying vegetable matter, as in a compost pile, presents no direct difficulties but does present problems with respect to aeration. Such materials pack so much, and the rate of oxygen consumption in the mass is so great, that it is impossible to keep the center of such a pile adequately supplied with oxygen unless aeration channels are provided. Hence, the common recommendation that the compost pile be turned from time to time if rapid decay is desired.

At the range of moisture contents of either soil or composts where moisture is limiting the growth of microorganisms, there is likely to be a change in the composition of the population. Bacteria and fungi usually, but not always, become relatively less abundant, whereas actinomycetes increase in numbers. The characteristic musty, or earthy, odor of moist hay serves as a definite manifestation of this take-over by these organisms. Furthermore, the surface of such materials is characteristically so covered with a mass of filaments of actinomycetes that the plant material assumes a grayish or whitish appearance. In this case oxygen is not the controlling factor because aerobic bacteria, fungi and actinomycetes all require abundant oxygen; the actinomycetes are merely able to carry on their metabolic activities with less moisture than can the other organisms.

Temperature

Temperature is a major factor in the decomposition of organic materials but affects different organisms in different ways. Each type of organism has its own growth range and optimum temperature. Within the range of growth between minimum and optimum it can be stated in a general way that for each rise of 10°C in temperature the metabolism and growth of a given organism is increased about 2- to 3-fold. In this respect microorganisms behave as do chemical reactions.

Since different organisms, and even different strains within a species, vary in their behavior with respect to temperature it is not possible to be very specific as to their response to it. Microorganisms are commonly arranged in two groups: the mesophilic bacteria, actinomycetes and fungi that grow in the range of 0 to about 40 or 45°C, and the thermophilic bacteria and actinomycetes that grow best at 45–60°C. A few thermophilic fungi have been isolated but they are not common soil inhabitants. Many thermophilic organisms can make some growth at lower temperatures but thrive only at the true thermophilic range. The optimum growth temperature for any organism is commonly within a few degrees (3–8°C) of its upper limit of growth.

The progress of organic matter decomposition is similar at the various temperatures except that the rate of tissue breakdown and carbon dioxide evolution is much greater at the higher temperatures. An exception to this statement may occur when a change in temperature brings about a very different predominant microflora, such as a shift from chiefly bacteria to actinomycetes or fungi. The shift from mesophilic to thermophilic forms without a marked shift in the types of organisms (bacteria, actinomycetes and fungi) usually has only a minor effect other than on the rate of decomposition.

When the temperature drops, as during the winter months, to 0°C and lower a few organisms may be killed but most of them merely remain dormant until the temperature is again within their growth range. They can withstand temperatures far below 0°C without being affected markedly.

There have been claims that temperature changes markedly affect the quantity of humus formed and the quantity of nitrogen released as ammonia. As already emphasized, there is a marked change in rate but unless the environmental conditions and composition of the micropopulation alter radically there is little evidence that the final product is appreciably changed. So long as there is a compound present that some organism can utilize as a source of energy and nutrients, its enzyme system will be active if growth conditions are favorable. Initially, the residue will be chiefly microbial cells, lignin-like substances and minerals; these may then undergo further changes and react enzymatically and chemically to form substances, largely colloidal, that we commonly designate as humus.

Reaction or pH

Reaction, which is one of the most important factors that affect decomposition and the whole process of humus formation, exerts its effect in a variety of ways, both direct and indirect. In the first place it affects the kinds of crops that grow on a soil and consequently the plant residues returned to the soil. Acid soils are base-deficient, whereas neutral soils are well supplied with calcium, magnesium, etc. Most legumes, which are base-loving plants, will not grow on very acid soils; many grasses will grow under either condition. Legume residues not only have more basic elements, but usually contain more protein, and hence are likely to have less lignin and a narrower carbon–nitrogen ratio. These differences in composition of the residues will of course have an influence on the rate and extent of their conversion into humus.

High pH values and high nitrogen in the crop residues favor bacteria, whereas low pH values and low nitrogen favor the growth of fungi. Bacteria usually grow more rapidly than fungi and convert a higher percentage of the organic matter into carbon dioxide and ammonia. The result is that the humification process may be delayed where fungi prevail and the final product, humus, is likely to be a little different, at least initially. Eventually, the fungal hyphae will also be decomposed and the final product will not differ markedly regardless of the intermediate steps in decay. In arable soils it is the rate of change and the steps in the process that are most affected by pH.

Acidity is undesirable in compost piles for much the same reasons that it is to be avoided in field soils. Hence, the common practice of adding lime or other basic materials to the compost pile to hasten decomposition and to assure that the final product will be in the best possible physical and chemical condition.

When both acidic and anaerobic conditions prevail, as occurs in many peat bogs prior to drainage and cultivation, almost all decomposition can be stopped. In such cases the constant formation of organic acids and other end products of anaerobic decomposition, such as methane, hydrogen sulfide and hydrogen, suppress the growth of nearly all aerobes including acid-tolerant fungi. Regardless of this a certain amount of humus and humus-like products are formed under these conditions that do not differ markedly from those formed in arable soils.

Aeration

The oxygen supply to decomposing organic matter determines to a considerable extent the nature of the microflora that brings about the decomposition, the rate at which it decomposes, and the final products. If only limited amounts of oxygen are present the decomposition process is likely to be delayed but eventually the normal aerobic breakdown products, chiefly carbon dioxide, ammonia and water plus the resistant lignin-like materials and microbial cells, will be formed. However, if oxygen is completely absent, then only anaerobic bacteria will be active and the products will be organic acids, some carbon dioxide, hydrogen, methane, hydrogen sulfide and the resistant plant materials that anaerobes cannot utilize. Under field conditions in arable soils anaerobic conditions are usually caused by waterlogging and are of short duration. As soon as the excess water drains away, the intermediate products, chiefly organic acids, are quickly oxidized to the usual aerobic products.

Inhibitory substances

It is now well established that many soil bacteria, fungi and actinomycetes produce antibiotics in their normal growth processes (Stallings, 1954; Pinck et al., 1961a,b, 1962). In fact, most of our antibiotics used in medicine are produced by organisms that were isolated from soils. There is, however, little quantitative proof that such antibiotics are produced in more than traces under average field conditions. When they are produced in soils in appreciable amounts it is always following the addition of energy sources, such as green manures and crop residues. The failure to be able to isolate the antibiotics may be due to inadequate analytical methods, to their destruction by other organisms, or to their being sorbed by clays. The latter factor seems to be the most important (Soulides et al., 1961, 1962). It is now generally believed, although not proven, that antibiotic production by a given microorganism plays a very important role in its ability to compete with other organisms. If so, then antibiotics may at times affect the extent and rate of decay. Eventually it is likely that the end products are similar irrespective of antibiotic production but the intermediate stages may be affected (see Chapter 18).

Tannins have been shown to retard markedly the decomposition of organic substances. Basaraba and Starkey (1966) observed that chestnut and wattle tannins formed complexes with gelatin and gliadin and thereby reduced the rate of decomposition of the proteins. The effect of tannin on the decomposition of peptone and an amino acid was much less. Similar studies by Benoit and Starkey (1968) with wattle tannin and various enzymes also showed marked inhibition. Urease was almost completely inactivated when the tannin–urease ratio was 1/10, whereas for a similar degree of inactivation a ratio of

55/1 was required for polygalacturonase and 117/1 for cellulase. Lewis and Starkey (1968 and 1969), in studies with various complexes, found that stability was a function of resistance of the tannin portion of the complex; resistance increased as the molecular weight of the tannin increased. Experiments involving the incorporation of tannins and various plant constituents into soil showed considerable inhibition of microbial attack on starch, chitin and saponin and to a lesser extent on pectin. Undoubtedly the presence of tannins does increase the resistance to decomposition of plant materials in soils but tannins probably play only a minor role in the accumulation of humus. In fact, as they are decomposed, even if slowly, the tannin residual breakdown products are subject to reaction with other compounds, or to polymerization, to form humus.

Other inhibitory substances may also gain entrance to the soil and affect the decay process. These include the accumulation of end products of biological action, excess salt concentration from fertilizers or from alkali soils, and pesticides or herbicides. None of these, except excess alkali in dry regions, are likely to be important in the decomposition process, since many species are involved with widely different tolerances for harmful substances.

PRODUCTS OF DECOMPOSITION

The original plant and animal substances that find their way into the soil consist chiefly of cellulose, hemicellulose, sugars, protein, lignin, fats, waxes, resins, and miscellaneous tannins, glucosides, alkaloids, pigments, etc. The cellulose, hemicellulose and proteins are fairly easily decomposed by enzymatic action into their building stones consisting chiefly of hexose and pentose sugars, uronic acids, peptides and amino acids. Lignin is not readily hydrolyzed to simple compounds but is slowly decomposed, chiefly by a few species of fungi. The fats, waxes, resins, tannins, etc. are also somewhat resistant but not immune to biological attack.

Under normal aerobic conditions most intermediate breakdown products are rather rapidly oxidized, chiefly to carbon dioxide, water, ammonia, phosphates and sulfates. The residue consists chiefly of partially demethoxylated lignin and microbial cells. The nitrogen not released as ammonia remains largely in the form of protein in the bacterial cells. For protein synthesis, microorganisms may use either the nitrogen of the decomposing organic substances or inorganic nitrogen from the soil solution (Sørensen, 1966). Released ammonia does not normally remain long in this form, but most of it is oxidized to nitrites and nitrates. A small portion may be held for a time in the clay lattice or may react with organic matter to form compounds that are resistant to biological attack (see Chapter 11).

Where anaerobic conditions prevail, oxidation is largely prevented and the simple end products mentioned do not form to any appreciable extent. Carbon dioxide is formed by anaerobic fermentation, but in much smaller quantities than under aerobic conditions. The final undecomposed product then contains much cellulose, hemicellulose and lignin with much of the original plant protein still present in the partially decomposed material. This is what happens in peat bogs, and the product formed there is representative of what can be expected wherever oxygen is extremely deficient. In nature it is common for aerobic and anaerobic conditions to alternate, usually as the rainfall varies. In such cases an intermediate type of product is likely to form, but the tendency will be for fairly complete oxidation at a delayed rate.

BIOLOGICAL IMMOBILIZATION OF NITROGEN

The previous discussion has emphasized the speed at which fresh organic materials can be decomposed in soil. There is also the matter of completeness of decomposition of the readily decomposable fractions. For example, sugar added to soil may be completely decomposed within a week or less. Not all of the carbon of the sugar is lost as CO_2 but tests for sugars may be negative. A succulent green manure crop may lose 60% of its dry matter within 1 or 2 months and 70–80% within 6 months. A considerable portion of the remaining 20–30% consists of residual materials, chiefly modified forms of lignin, hemicellulose, waxes and other materials that may have partially resisted biological attack. In addition, there are the cells of living and dead microorganisms that were responsible for the decomposition processes. All of these materials may undergo further changes as they are transformed into humus.

Bacteria commonly contain 6–13% nitrogen that is present largely as protein in the cell contents, and chitin in the cell walls. Fungi and actinomycetes contain less nitrogen, and the percentage present is likely to vary widely depending on the nature and composition of the organic substances on which they grow. These cells of microorganisms are of course made up wholly of synthetic material and constitute a considerable and very active part of soil organic matter. The activity is not limited to living organisms, because the dead cells form a considerable portion of the colloidal portion of the soil that is responsible for many of the physical characteristics of soils.

Interrelationships between C, N, P and S

In discussions of the synthetic processes that occur when organic substances are undergoing decomposition the emphasis is usually placed on nitrogen. How much is released, or how much is utilized, by the organisms that are involved, and at what rate do these changes in available nitrogen occur? This emphasis on nitrogen largely reflects its great importance in crop production, for the supply of available nitrogen is commonly the chief factor that controls crop yields under suitable soil conditions for crop growth. But most of the other essential elements are also involved in these degradation and synthetic, or immobilization, reactions. This applies especially to C, P and S that are present in all living tissues in a more or less definite and constant relationship. Such a relationship would be expected since these three elements, together with nitrogen, are the major ones aside from hydrogen and oxygen that go to make up cell protoplasm. Other elements, such as iron, calcium, magnesium and the minor elements, are usually needed in much smaller amounts, and the quantities required vary widely with types of micro and macro forms of living organisms.

After decomposition processes have proceeded to the point where we have a comparatively stable form of soil organic matter there is still a reasonably consistent relationship between the elements, C, N, P and S. The ratio between the elements is not fixed but the four elements are always present, and losses or gains in one are likely to be accompanied by similar changes in the others.

The discussion that follows will deal primarily with the carbon–nitrogen relationship since this is the most important one involved, and the one that has received the most attention by research workers. The reader should bear in mind, however, that much of the accumulated information that bears on these two elements also applies to some extent to many of the relationships between all of the four elements discussed above.

Energy supply and carbon–nitrogen ratio

Biological mineralization and immobilization are proceeding at all times in soils maintained under crop growing conditions, whether a crop is present or not. As organic matter is being oxidized with the release of carbon dioxide and ammonia, the microorganisms present are using at least a small percentage of the released nitrogen for the formation of new cells. In soils that have not received fresh organic materials recently the amount of nitrogen being used for synthesis of the new microorganisms is small. Such soil organic matter is comparatively resistant to decay and the quantity decomposed is small; the number of new cells formed is correspondingly small. Under such conditions mineralization is dominant over immobilization; that is, more ammonia and nitrates accumulate than are utilized in synthesis. Both nitrogen release and nitrogen tie-up in microbial cells vary directly with ease of decomposition of the soil organic matter and with the amount present (Walunjkar et al., 1959).

The addition of easily decomposable organic materials to a soil changes the level of biological activity by factors of 10- to 50-fold. This increased activity, as already stated, is attributable almost entirely to the new supply of highly available energy sources. Under these new conditions there is also a close parallel between mineralization and immobilization; if the first is increased 50-fold, it is likely that the second will be increased similarly. Decomposition processes commonly convert 60% or more of the carbon in the added fresh plant materials into carbon dioxide and only 5–25% of the carbon is likely to be used initially in microbial cell synthesis. The quantity of nitrogen so used varies with the kinds of organisms present, their rate of multiplication and the time involved. The nitrogen content of microbial cells varies considerably with the substrate upon which they grow but the range for most soil bacteria is likely to be between 6 and 13%, and for fungi 3–6% (Waksman, 1932). Since we never have quantitative data on all of these factors, we must rely on empirical data for estimating the nitrogen demands in cell synthesis. Much data of this type are available and, considering that so many factors are involved, it is a little surprising that they agree so closely.

Many immobilization experiments (Pinck et al., 1946; Allison and Klein, 1962) show that if common crop residues have a carbon–nitrogen ratio of about 30–25 (1.4–1.7% N), or if nitrogen fertilizer is added to bring the nitrogen up to this level, decomposition can proceed at a maximum rate. Under these conditions there will usually be no immediate net release of mineral nitrogen from the crop residues. Addition of more fertilizer nitrogen than is required to bring the nitrogen up to this level will not further increase the rate of mineralization or of nitrogen immobilization. If the added plant material has a carbon–nitrogen ratio narrower than about 25, and is readily decomposed, then mineralization is likely to exceed immobilization and nitrogen will be released as ammonia. This commonly occurs following the addition to soil of a very young and succulent green manure crop, or of bluegrass clippings from the lawn.

In experiments conducted at 30°C for 10 weeks in soil, Power (1968) found that grass roots containing 0.84% nitrogen immobilized mineral nitrogen, whereas there was a net increase in mineral nitrogen where grass roots with 1.44% nitrogen were added. The changes in mineral nitrogen were in proportion to the amount of roots added.

Most crop residues have carbon–nitrogen ratios greater than the critical ratio of near 30 or 25 and hence when they are added to soils the result is a nearly complete tie-up of all available nitrogen, whether being released from the crop residue or from soil organic matter. This occurs commonly when straw, cornstalks, mature weeds, dry grasses and many kinds of sawdust are added to soils without supplemental nitrogen. Under such conditions the microorganisms usually grow at a rapid rate even though the nitrogen supply is suboptimal for their cell synthesis. In extreme cases their rate of growth is reduced, but more likely the nitrogen percentage in the new microbial cells is merely lower. These facts emphasize what has already been stated, namely that available energy supply is the main factor controlling microbial growth; the fate of the nitrogen, as well as of the carbon, phosphorus and sulfur is secondary.

Knowledge of the carbon–nitrogen ratio of organic materials being added to soils serves as an excellent index of what may be expected to happen after addition, but only if there is also knowledge of the approximate composition and characteristics of the added materials. We have this additional information for most crop residues, but when we apply the carbon–nitrogen ratio concept to other materials the result may be misleading. For example, in terms of behavior in the soil, the carbon–nitrogen ratio of comparatively inert materials, such as leather scraps, lobster shells, peat, and some urea–formaldehyde products, is meaningless. In contrast, the carbon–nitrogen ratio concept can be applied to organic materials that readily and completely decompose, such as proteins, sugars, and starches. This, again, emphasizes that we are concerned primarily with available energy and that knowledge of both carbon and nitrogen contents is of little value in the prediction of immediate effects in the soil if the materials do not decompose readily. Rubins and Bear (1942) emphasized these facts in connection with the nitrogen availabilities of organic fertilizer materials. They pointed out the necessity for eliminating lignin in con-

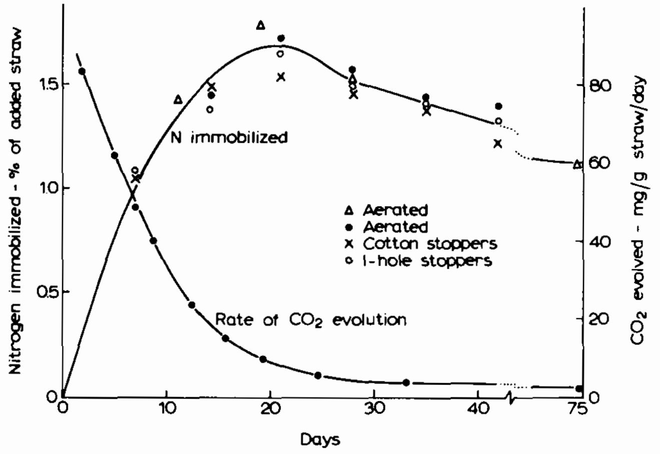

Fig.6.3. Immobilization and release of nitrogen, and rate of carbon dioxide formation, in a soil receiving wheat straw and nitrate nitrogen. (From Allison and Klein, 1962.)

sidering carbon–nitrogen ratios, since it decomposes so slowly.

The data of Allison and Klein (1962), presented in Fig.6.3, show the rates of decomposition of straw, immobilization of nitrogen, and subsequent release of the nitrogen that was either tied up by microorganisms or never released from the straw. In this experiment wheat straw, together with adequate nitrogen as sodium nitrate, was added to a sandy loam and incubated at constant temperature. Nitrogen immobilization was very rapid during the first week and reached a maximum after 20 days at 1.7% of the original weight of the straw. Immobilization closely paralleled decomposition as evidenced by carbon dioxide evolution.

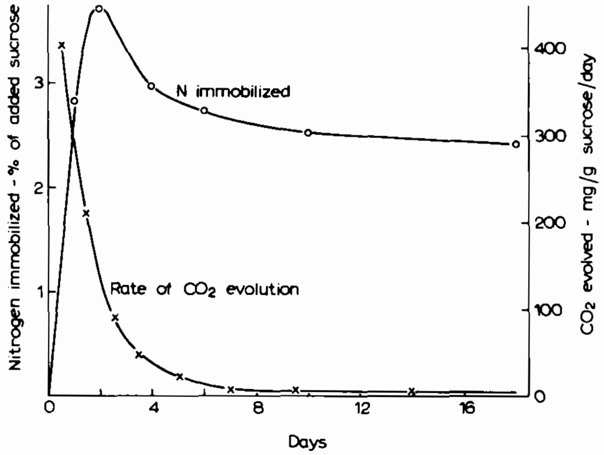

Fig.6.4. Immobilization and release of nitrogen, and rate of carbon dioxide formation, in a soil receiving sucrose and ammonium sulfate. (From data of Winsor and Pollard, 1956; graph drawn by Allison and Klein, 1962.)

Somewhat similar data of Winsor and Pollard (1956), in which sucrose and ammonium sulfate were added to a garden soil are shown in Fig.6.4, prepared from their data by Allison and Klein (1962). With this substrate, maximum immobilization occurred in 2 days instead of 20 days as with straw in Fig.6.3, and immobilization corresponded to 3.7% of the weight of the sugar in contrast to 1.7% with straw. Again immobilization was closely correlated with biological activity as evidenced by carbon dioxide evolution.

The data in Fig.6.3 and 6.4 serve as a striking demonstration of the importance of composition of the substrate on nitrogen immobilization. Sugar, which is rapidly and completely available as an energy source brought about more than twice as much nitrogen immobilization, based on weight of substrate, as did straw that contains considerable slowly-available materials. Reference will be made to the rate of release of the tied-up nitrogen in a subsequent section.

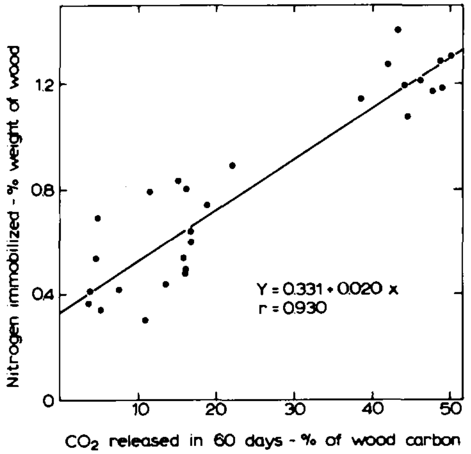

Fig.6.5. Relationship between maximum observed nitrogen requirements in wood decay and carbon dioxide evolution during a 60-day incubation period. (From Allison et al., 1963.)

The results of studies of the maximum immobilization of nitrogen by sawdusts prepared from 19 softwoods and 9 hardwoods are shown in Fig.6.5. These experiments (Allison et al., 1963), conducted in the same manner as those shown in Fig.6.3, show nitrogen tie-up values in the range of 0.3–1.4% of the original dry weights of the woods. In Fig.6.5, where the immobilization values are plotted against total carbon dioxide evolved in 60 days, there is a high degree of correlation. The low values for nitrogen immobilized are as expected, since woods decompose only partially and at comparatively slow rates. The maximum immobilization values for the ten woods that decomposed most rapidly were usually reached in about 40 days; the corresponding time for the slowly decomposing woods was usually in the range of 80–160 days.

The effect of straw on the nitrogen content of wheat grown in the greenhouse during the winter months is shown in Fig.6.6 (Pinck et al., 1946). In this experiment so much nitrogen was immobilized by the microorganisms that decomposed the straw that the

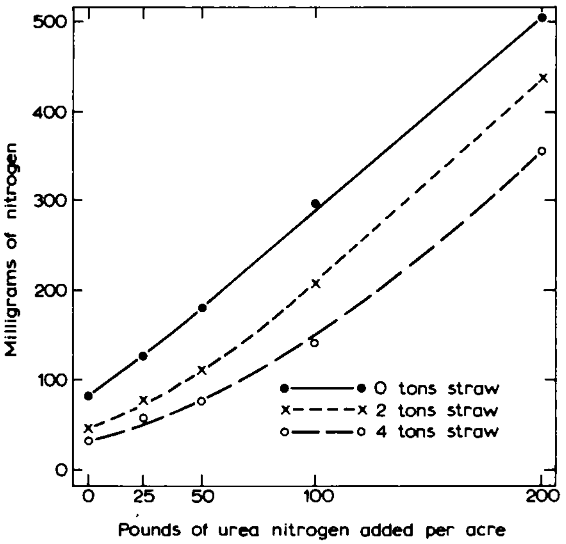

Fig.6.6. The effects of straw and urea upon the nitrogen content of wheat planted in the greenhouse in winter immediately after mixing with the soil. (From Pinck et al., 1946.)

yields and nitrogen content of the wheat crop were markedly depressed in the absence of outside nitrogen. When the carbon–nitrogen ratio of the straw was narrowed to 35 (1.2% N) by the addition of urea there was no depressing effect of the straw additions. In a similar experiment, conducted in the warm summer months, the carbon–nitrogen ratio had to be lowered to 27–31 (1.56–1.37% N) in order to avoid decreased nitrogen supply to the crop.

Growing plants serve as a constant source of energy for soil microorganisms. Apart from the root mass, there is considerable sloughed-off root material and root hairs that are constantly deteriorating and being replaced by new cells. Plant roots also secrete or excrete a large number of compounds that are excellent food sources (Rovira, 1962), although the total quantity of these may be comparatively small (see Chapters 5 and 18). We do know, however, that they are not negligible for if so we would not have the marked proliferation of microorganisms in the rhizosphere. Where the growth of microorganisms is so much in evidence we know that nitrogen immobilization is paralleling their numbers very closely. The amount of nitrogen so immobilized, as well as numbers of microorganisms in the rhizosphere, varies widely with plant species, rate and amount of growth, stage of growth, soil conditions, and relative abundance of available nitrogen. Jansson (1958) and Winsor (1958) have presented good discussions of our knowledge of mineralization and immobilization.

The use of the heavy nitrogen tracer technique has helped materially in our understanding of the extent to which immobilization occurs. Among the first to use this technique were Hiltbold et al. (1951) who observed that during the period of rapid growth of oats, immobilization of nitrogen into soil organic matter was 2–4 times greater in cropped than in uncropped soils. In earlier non-tracer experiments Goring and Clark (1948) had emphasized the role that plants with their rhizosphere microflora play in the immobilization of available nitrogen to form soil organic matter. The tracer data of MacVicar et al. (1951), and of Bartholomew and Hiltbold (1952), are in general agreement with the ideas presented above.

Jansson (1955, 1958) has emphasized the preferential use of ammonia by soil microorganisms. This is usually true when both ammonia and nitrate nitrogen are present at the same time but this fact is of minor importance. Many workers (Stojanovic and Broadbent, 1956; Walunjkar et al., 1959; Allison and Klein, 1962; Broadbent and Tyler, 1962) have shown that either nitrate or ammonia nitrogen is readily immobilized and thus converted into soil organic matter.

When plant materials are decomposed to form soil organic matter, what happens to the plant protein; is it almost completely decomposed and the organic nitrogen converted into microbial protein to the extent needed by the microorganisms, or does a considerable portion of it resist decomposition and remain as residual material in the soil humus? This question cannot be answered with complete certainty. Bartholomew (1965) discusses the available information from tracer experiments where tagged inorganic nitrogen was added to decomposing crop residues, and concludes that "the strong tendency toward tracer equivalence in the organic and inorganic phases in studies of this nature, and the occurrence of essential equivalence in at least one instance, are strong evidence that plant protein is largely or completely decomposed in the decomposition process and that the organic nitrogen which remains with the residue is largely microbial in origin."

Tracer studies conducted in flooded soils by Broadbent and Nakashima (1970) showed that immobilization values were intermediate between those obtained under aerobic and anaerobic conditions. Rice straw containing 0.47% nitrogen immobilized an additional 0.5% nitrogen, whereas straw containing 1.17% nitrogen immobilized 0.43% nitrogen. In such studies with a low-nitrogen plant material there is little tendency for release of any of the original nitrogen of the straw. Hence, the quantity of tagged nitrogen found in organic form is a measure of net immobilization, provided there is no appreciable amount of untagged soil nitrogen being made available.

Release of immobilized nitrogen

The term immobilized nitrogen, if strictly defined, refers to the nitrogen that is assimilated by the microorganisms that decompose organic materials that are added to soil or formed in it. The previous discussion has shown how, and to what extent, this takes place under different conditions. In attempts to study the rate of release of this immobilized nitrogen we are confronted with the fact that under practical soil conditions we never have only immobilized nitrogen present. It is usually present in intimate mixture with other nitrogen that is also being made available. These other sources of nitrogen may include: (1) the slowly available portion of the nitrogen being released from plant and animal residues, and that has never been assimilated by microorganisms; (2) nitrogen that was chemically fixed by clays and organic matter (see Chapter 11); and (3) nitrogen added as fertilizer that for various reasons was not completely utilized by the previous crop. About the only way to have immobilized nitrogen only is to grow microorganisms in pure culture on a substrate, such as sugar, that is completely assimilated. Many data obtained by the use of such a procedure are available, but do not furnish much information on what is happening in a soil.

The ^{15}N-tracer technique has been used successfully in studies of the rate of release of nitrogen immobilized in the cells of microorganisms (see Tyler and Broadbent, 1958; Broadbent and Tyler, 1962; Jansson, 1963; Bartholomew, 1965; Broadbent and Nakashima 1965, 1967). There is general agreement that immobilized nitrogen resists mineralization for rather long periods of time. Jansson observed that net mineralization of such nitrogen amounted to only 3.0–4.7% per year. The work of Stewart et al. (1963a,b) agrees closely with these data. The immobilized nitrogen becomes progressively less available with time probably because the nitrogenous compounds are constantly being converted into compounds of greater biological stability. At the present time there is no completely satisfactory explanation for the observed facts. Bremner (1955) found that nitrogen synthesized in composts is there largely as protein and a much smaller portion as amino sugars, but no explanation for the resistance to decomposition was found. Recently, Bremner (1965) hypothesized that there is a chemical association between microbial protein and non-protein materials that protects the former. In addition, it is also possible that the protein in microorganisms, which is not especially resistant to decay, undergoes decomposition and the breakdown products react with ring compounds to form the very resistant nitrogen compounds in humus that the various workers mentioned above have observed.

In Fig.6.3, where straw and adequate nitrate nitrogen were added to a soil, it will be noted that after 20 days nitrogen to the extent of 1.7% of the weight of the straw was immobilized but after 60 days this value had decreased to about 1.1%. This decrease does not indicate that a large percentage of the microbial cell nitrogen was mineralized. During this 20–60-day period there was probably as much or more straw nitrogen present as microbial nitrogen, and this straw nitrogen was still undergoing mineralization at an ever-decreasing rate. The work cited above, where tracer nitrogen was added, might indicate that the decrease in tie-up of nitrogen during the 40-day period shown in Fig.6.3 was largely from the straw residue. Nevertheless, it is also probable that the young microbial cells did lose a portion of their nitrogen either just before or after death, which is not uncommon for many bacterial species. The author has observed such a release of nitrogen amounting to 10–20% from cells of *Azotobacter vinelandii* and *Nostoc muscorum* in pure culture during the few days subsequent to maximum growth. Among the more resistant nitrogen compounds that would be retained would be cell-wall chitin; and this substance is so resistant to decay that it might protect the protein inside cells from rapid decomposition. Fig.6.4, where sucrose was the substrate, also showed a release of about 25–30% of the immobilized nitrogen shortly after maximum growth was attained. These data would indicate even more strongly than those in Fig.6.3 that appreciable nitrogen was lost from the young microbial cells. Such an explanation is not necessarily in conflict with the tracer data where the experimental period was often considerably longer, and any early loss from cells may not have been determined by the techniques used. Neither is this explanation out of harmony with Bremner's (1965) hypothesis for he was thinking more in terms of the long-time stability of microbial nitrogen.

Bartholomew (1965) in his discussion of the subject states that the accumulated data support the hypothesis that "as decomposition processes continue in plant residues, some protective reactions occur which render the microbially produced organic nitrogen more resistant to further decomposition than it would otherwise be if it were apart from the environment of the partially decomposed plant substance. The mechanisms involved are still matters of conjecture." In the author's opinion this is a good summary of the present status of the subject (see further discussion in Chapter 8).

REFERENCES

Allison, F.E. and Cover, R.G., 1960. *Soil Sci.*, 89: 194–201.

Allison, F.E. and Klein, C.J., 1962. *Soil Sci.*, 93: 383–386.

Allison, F.E., Murphy, R.M. and Klein, C.I., 1963. *Soil Sci.*, 96: 187–190.

Bartholomew, W.V., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 285–306.

Bartholomew, W.V. and Hiltbold, A.E., 1952. *Soil Sci.*, 73: 193–201.

Basaraba, J. and Starkey, R.L., 1966. *Soil Sci.*, 101: 17–23.

Benoit, R.E. and Starkey, R.L., 1968. *Soil Sci.*, 105: 203–208.

Bhaumik, H.D. and Clark, F.E., 1948. *Soil Sci. Soc. Am. Proc.*, 12: 234–238.

Bremner, J.M., 1955. *J. Agric. Sci.*, 45: 469–475.

Bremner, J.M., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 93–149.

Broadbent, F.E. and Nakashima, T., 1965. *Soil Sci. Soc. Am. Proc.*, 29: 55–60.

Broadbent, F.E. and Nakashima, T., 1967. *Soil Sci. Soc. Am. Proc.*, 31: 648–652.

Broadbent, F.E. and Nakashima, T., 1970. *Soil Sci. Soc. Am. Proc.*, 34: 218–221.

Broadbent, F.E. and Tyler, K.B., 1962. *Soil Sci. Soc. Am. Proc.*, 26: 459–462.

Goring, C.A.I. and Clark, F.E ., 1948. *Soil Sci. Soc. Am. Proc.*, 13: 261–266.

Hiltbold, A.E., Bartholomew, W.V. and Werkman, C.H., 1951 *Soil Sci. Soc. Am. Proc.*, 15: 166–173.

Jansson, S.L., 1955. *Z. Pflanzenernähr. Düng. Bodenkd.*, 69: 190–198.

Jansson, S.L., 1958. *Ann. R. Agric. Coll. Swed.*, 24: 101–361.

Jansson, S.L., 1963. *Soil Sci.*, 95: 31–37.

Lewis, J.A. and Starkey, R.L., 1968. *Soil Sci.*, 106: 241–247.

Lewis, J.A. and Starkey, R.L., 1969. *Soil Sci.*, 107: 235–241.

Lockett, J.L., 1937. *Soil Sci.*, 44: 425–439.

MacVicar, R., Garman, W.L. and Wall, R., 1951. *Soil Sci. Soc. Am. Proc.*, 15: 265–268.

Miller, R.D. and Johnson, D.D., 1964. *Soil Sci. Soc. Am. Proc.*, 28: 644–646.

Nikiforoff, C.C., 1938. *U.S. Dep. Agric., Yearb. Agric., 1938:* 929–939.

Pinck, L.A., Allison, F.E. and Gaddy, V.L., 1946. *J. Am. Soc. Agron.*, 38: 410–420.

Pinck, L.A., Holton, W.F. and Allison, F.E., 1961a. *Soil Sci.*, 91: 22–28.

Pinck, L.A., Soulides, D.A. and Allison, F.E., 1961b. *Soil Sci.*, 91: 94–99.

Pinck, L.A., Soulides, D.A. and Allison, F.E., 1962. *Soil Sci.*, 94: 129–131.

Power, J.F., 1968. *Soil Sci. Soc. Am. Proc.*, 32: 673–674.

Rovira, A.D.,. 1962. *Soils Fert.*, 25: 167–172.

Rubins, E.J. and Bear, F.E., 1942. *Soil Sci.*, 54: 411–423.

Russell, E.W., 1961. *Soil Conditions and Plant Growth.* Longmans and Green, London, 9th ed., XVI, 688 pp.

Sørensen, H., 1966. In: *The Use of Isotopes in Soil Organic Matter Studies.* Pergamon, New York, N.Y., pp. 271–274.

Soulides, D.A., Pinck, L.A. and Allison, F.E., 1961. *Soil Sci.*, 92: 90–93.

Soulides, D.A., Pinck, L.A. and Allison, F.E., 1962. *Soil Sci.*, 94: 239–244.

Stallings, J.H., 1954. *Bacteriol. Rev.*, 18: 131–146.

Stewart, B.A., Porter, L.K. and Johnson, D.D., 1963a. *Soil Sci. Soc. Am. Proc.*, 27: 302–304.

Stewart, B.A., Johnson, D.D. and Porter, L.K., 1963b. *Soil Sci. Soc. Am. Proc.*, 27: 656–659.

Stojanovic, B.J. and Broadbent, F.E., 1956. *Soil Sci. Soc. Am. Proc.*, 20: 213–218.

Tyler, K.B. and Broadbent, F.E., 1958. *Soil Sci. Soc. Am. Proc.*, 22: 231–234.

Van Schreven, D.A., 1964. *Plant Soil*, 20: 149–165.

Waksman, S.A., 1932. *Principles of Soil Microbiology.* Williams and Wilkins, Baltimore, Md., 2nd ed., 894 pp.

Waksman, S.A. and Tenney, F.G., 1927a. *Soil Sci.*, 24: 275–283.

Waksman, S.A. and Tenney, F.G., 1927b. *Soil Sci.*, 24: 317–333.

Waksman, S.A. and Tenney, F.G., 1928. *Soil Sci.*, 26: 155–171.

Walunjkar, W.G., Bartholomew, W.V. and Woltz, W.G., 1959, *J. Indian Soc. Soil Sci.*, 7: 65–72.

Weiss, F.J., 1955. *J. Agric. Food Chem.*, 3: 388–398.

Winogradsky, S., 1925. *Ann. Inst. Pasteur*, 39: 299–354.

Winsor, G.W., 1958. *J. Sci. Food Agric.*, 9: 792–801.

Winsor, G.W. and Pollard, A.G., 1956. *J. Sci. Food Agric.*, 7: 134–149; 613–624.

Chapter 7

THE ORGANIC MATTER CONTENT OF SOILS

INTRODUCTION

The organic matter content of a mineral soil is dependent on many factors that exert their effects both individually and collectively, and to varying degrees. A marked change in one factor may cause marked changes in the effects of other factors, and hence in the over-all net carbon accumulation. In virgin soils untouched by man these changes usually occur very slowly, perhaps requiring several centuries to bring about a marked change in the amount or distribution of the organic matter in the soil profile. Actually, under natural conditions, marked changes in organic matter content in the soil usually occur only if there is a major change in climate, which in turn affects the nature of the vegetation. The activities of man, which usually means the removal or marked modification of the vegetative cover and the use of the moldboard plow, greatly speed up the changes in the organic matter level. These changes brought about by man usually lead to an initial rapid lowering of the organic matter content.

Under stabilized environmental conditions, whether in the virgin soil or the cultivated soil, there is eventually established a fairly constant level of organic matter. This state of equilibrium is reached when carbon loss, chiefly as carbon dioxide, balances the gain through additions of vegetable matter. Such an equilibrium may be reached under some soil conditions when the soil contains less than one percent of organic matter; under other conditions there may be 10% or more. Under very extreme conditions, where drainage and soil aeration may be unsatisfactory, the soil may contain more organic matter than mineral matter, in which case it is classed as a muck or peat (Chapter 29 and 30).

In the discussion that follows, the more important factors that determine the extent to which organic carbon commonly increases or decreases in soil are considered. The natural environmental factors, and also modifications brought about by man in his endeavor to produce abundant crops with the minimum expense for labor and materials, are discussed.

ORGANIC MATTER DISTRIBUTION IN THE PROFILES OF VIRGIN SOILS

A consideration of the organic matter distribution in the profiles of our main types of virgin soils is necessary in order to understand the conditions that now exist in our agricultural soils. Although many years removed from the virgin condition, cultivated soils may still retain many of the characteristics of the original soils, and these native characteristics markedly influence the management when used for crop production.

Forest soils

In discussing profiles it is fairly common for writers to lump together those formed under forests, including some shrubs, and call the resulting soil a podzol. In a sense this is correct but certainly the soils formed under these conditions are not all alike. Some are typical podzols, others are only podzol-like, whereas others show little resemblance to true podzols (see discussion by Muir, 1961). Both vegetative cover and climate are major factors that determine the characteristics of the profiles. The nature of the soil markedly affects the plant population and, likewise, the plant population affects the soil that is produced. This effect of the vegetation on the soil usually reaches its peak under natural conditions only after a few centuries, and probably after the stage commonly designated as climax vegetation is reached.

The most typical podzols are usually those formed under coniferous forests; less typical are the podzol-like soils formed chiefly under deciduous forests or in a warm climate. In many areas of the United States these two types of vegetation occur in mixture and the resulting soil shows characteristics that are intermediate between the two. In other cases, where man has interfered with nature, deciduous trees may follow coniferous ones, or the reverse. The podzol-like soils are commonly referred to as either gray-brown forest soils of the Temperate Zone or red and yellow podzolic soils of the warmer regions.

Organic matter plays a major part in the development of the podzol profile. In fact, the first essential for the development of a true podzol is that there be deposited a considerable layer of leaves, needles, cones and dead twigs on the soil surface. The debris from coniferous trees is far more resistant to attack by microorganisms than is that from deciduous trees, and pine needles and cones are not nearly as satisfactory a food for earthworms and other small animals as are the leaves from deciduous trees. As a result, coniferous vegetation tends to accumulate on the soil surface as an undecayed peat-like mass, designated as duff or mor. In contrast, deciduous vegetation is an excellent food for both the animal and microflora populations. If the soil is not appreciably acid the fauna, chiefly earthworms, continually carry these easily digested leaves into the soil and mix them with the upper foot or so of soil. The organic mat, if any, is therefore usually more decomposed and limited in amount. If it is humus-like and granular in structure, it is customary to designate it as a mull. Since the development of a true podzol is dependent upon a heavy accumulation of organic matter at the surface it is obvious why the most extreme podzols are found in coniferous forests and not in deciduous ones.

In Finland, for example, where typical podzols are predominant, the forest soils have a humus layer of varying thickness with even larger amounts found in the upper portion of the mineral soil. Viro (1963) states that over 95% of the tree roots are found in the humus layer and the upper foot of mineral soil. In south Finland the humus layer of the pine stands may contain nearly two tons of nitrogen per hectare, and the spruce stands still more. Most of this nitrogen is of course in an unavailable form. Under the climatic conditions prevailing in Finland, where leaching is curtailed, the conditions favor the accumulation of both humus and nitrogen in the upper layers.

The process of podzolization, which occurs in both temperate and tropical climates, is brought about primarily by the downward movement of water through the surface organic layer carrying with it dissolved organic acids, iron and aluminum compounds, bases, and also considerable clay and other colloidal material. This constant extraction of the soil commonly leaves a bleached soil layer immediately below the surface organic layer. Much of the material so removed is deposited below the white layer but usually at different levels of the profile. Most of the organic matter is deposited as a black layer just below the whitened layer and contrasts sharply with it. The iron and aluminum compounds are deposited both with the organic matter and below it, and act as cementing materials. In extreme cases the cementing process results in a thin, impervious layer that we call a hardpan. Considerable clay in suspension is carried to greater depths depending on the texture of the main soil mass. Most of the bases, particularly calcium, that are extracted by the water containing humic acids are removed completely from the soil profile. This constant extracting and leaching process characteristically results in acid soils of low fertility and with distinct A- and B-horizons, which can vary considerably in width.

Podzol-like soils formed in deciduous forests, where there is less resistant surface organic debris, are much less extracted. Deciduous trees assimilate more soil bases from the subsoil than do coniferous trees, and since the leaves decay more readily there is a constant return of bases from the subsoil to the surface, thereby offsetting in part the downward movement in the drainage. These podzol-like soils may have no bleached layer and much less distinct horizons than the true podzols. They are less acid, more fertile than the typical well-developed podzol, and the organic matter is more mixed with the soil mass. Typical podzols have little or no granular structure, whereas the gray-brown soils often have a fairly well-developed crumb structure.

In the warmer regions, where red and yellow lateritic type soils occur, organic matter decomposition proceeds more rapidly and completely, and leaching is more intense than in the temperate regions (Sivarajasingham et al., 1962). The soil profile is less developed and fertility is low. In these soils hydrolysis of rock minerals occurs to such an extent that the final soil material consists largely of aluminum and iron hydroxides together with varying amounts of silicic acid. In the formation of lateritic soils the podzolization process occurs during formation but the fully-developed soil profile is very different from the typical podzols formed in colder regions.

Grassland soils

Soils formed in areas where a constant cover of grass has been present for hundreds of years are usually among the most fertile of all of our agricultural soils and, apart from organic soils, have the highest humus contents of any. The soil organic matter content of the most well-developed grassland soils, designated as chernozems, is commonly within the range of 3–6%, and occasionally as high as 10% in the surface layer. The organic matter content progressively decreases with depth but is often surprisingly high even to a depth of 2–4 ft.

Chernozem and chernozem-like soils are commonly found in subhumid climates of the Temperate Zone where the annual rainfall is usually too low for a dense tree population to be established. In the United States these soils are found chiefly in the eastern Dakotas and Nebraska and extending south into central Kansas and Oklahoma. Other soils designated as chestnut, and somewhat similar, are found in a drier zone to the west of the chernozems. Since the rainfall is less and the vegetation more sparse, these chestnut soils are usually lower in organic matter than are the chernozems. Deficient moisture, however, retards decomposition and this favors organic matter retention.

Under a continuous cover of grass, and limited rainfall, the surface of virgin grasslands is always covered with a heavy layer of growing plants and dead residues. The main mass of roots of the grasses extends to a depth of 6–12 inches and forms a rather compact sod consisting mostly of fibrous roots. Under natural conditions all of this mass of tops and roots stays on or in the soil until it decays and of course most of the nutrients absorbed by the roots remain in the surface layer. Organic matter extends to a considerable depth because the roots penetrate to these depths and the residues remain. Some organic matter from the decaying surface mat also moves into the subsoil, but such movement is limited because under the rainfall conditions there is no large volume of water moving through the profile. There is some movement, however, but usually only to a depth of a few feet and this results in the process designated as calcification. This involves the solution of some of the calcium in the calcium-rich grass residues in the surface foot and its deposition in part, at least, at lower depths. The depth of movement of calcium and some magnesium usually corresponds to approximately the depth to which surface waters usually move, but such deposits do not always occur. The abundance of calcium in the soil profile serves to keep the colloidal clay in a flocculated condition and it does not move downward as it does in non-aggregated podzol profiles. The result is the formation of a nutrient-rich, high-in-organic matter, non-leached, well-aggregated soil with only a limited distinction between horizons. If much calcium is deposited in the subsoil there may be a visible stratification but even this calcium may not be deposited in distinct layers but rather in channels where the water usually moves.

Prairie soils

Lying between the broad belt of the eastern podzols and the western chernozem soils are the prairie soils, often designated as the Corn Belt soils. As would be expected, there are all gradations between the two groups on either side. Most of these prairie soils received enough rainfall for considerable leaching to occur and for the removal of the calcium into the drainage waters. Calcium deposits in the lower horizons are seldom found. These soils are commonly well supplied with minerals and have rather deep profiles, that do not differ greatly from those of chernozems and chestnut soils. Organic matter extends downward into the profile in much the same manner as that in the chernozems, and a granular structure is usually present. Where the rainfall is highest the profile characteristics tend to be much like those produced by podzolization. These Corn Belt soils are recognized as among the most productive, due not only to their basic characteristics but also to a yearly rainfall adequate to produce more vegetation than is possible in the subhumid regions farther west.

Desert soils

Desert soils are of course of no great interest agriculturally except when irrigated. These hot and dry soils naturally support only sparse vegetation consisting mostly of shrubs and a few grasses. Annual organic residues left by such plants are extremely small and the organic matter content of the soils is very low, derived largely from the few roots that are formed. These roots penetrate to unusual depths through the loose soil material. Since desert soils are not leached, their content of mineral nutrients other than nitrogen is high and the profile is often uniform down to depths of several feet. When supplied with water and nitrogen they are usually very productive except where alkali salts, especially sodium carbonate, have accumulated to such an extent as to be toxic.

Fuller et al. (1960) state that soils developed under arid and semiarid conditions are characteristically low in nitrogen and this element is usually the major one that is limiting under irrigated conditions. Virgin soils of Arizona contain only 0.1–1% organic matter as compared with 3–5% in the prairie soils of the Midwest. This low organic matter content does not seriously limit crop yields under irrigated conditions, provided adequate fertilizer nitrogen is applied.

CARBON–NITROGEN RELATIONSHIPS IN SOIL ORGANIC MATTER

The carbon content of soil organic matter was early determined by the combustion method to be about 58%, and from this value it follows that the organic matter content of a soil can be obtained by multiplying its carbon content by the factor 1.724. This procedure has been much used, even though it is not accurate, and has been much criticized. Broadbent (1953), for example, presents data for 63 surface soils showing that the factor varied between 1.6 and 3.3 with the bulk of the values falling in the range of 1.8–2.0. He concludes that if a factor is to be used a value of 1.9 is more satisfactory than 1.7. If extreme accuracy is not required, there is certainly no objection to the use of a factor, at least in discussions such as given here. Sometimes it is very advantageous to do so, since more soil scientists express their results in terms of organic carbon than as soil organic matter. The writer will make use of the conventional factor (1.724) whenever it seems advantageous to do so.

Nitrogen is always present as a constituent of soil organic matter. The usual ratio of carbon to nitrogen in the large majority of cultivated soils is between 10 and 12. Ratios below 10 are sometimes found in the warmer and drier soils but such narrow ratios are not common in our most productive soils. Ratios above 12 are fairly common both in colder soils where decomposition is retarded, and also in nitrogen-deficient warmer soils where for any reason carbonaceous residues tend to accumulate. Sometimes wide ratios may be due in part to the presence of elemental carbon that accumulates as a result of frequent burning of the vegetation. In this case the ratios are of course misleading since they are not true soil organic matter ratios.

The carbon–nitrogen ratio of soil organic matter is not nearly as constant as is the carbon content and hence it is not advisable to multiply the nitrogen content by an undetermined ratio, such as 10 to 12, to obtain the soil carbon content. It is much less advisable to obtain the organic matter content from the nitrogen analysis by multiplying the latter by some assumed carbon–nitrogen ratio times 1.724. However, it is helpful to bear in mind that as a rough approximation the organic matter content of most of our agricultural soils is commonly about 20 times its nitrogen content.

ORGANIC MATTER IN REPRESENTATIVE SOILS

Although considerable general information is given above on the origin, distribution, and relative abundance of organic matter in our main agricultural soils, and the reasons for these differences, it is well to present some more quantitative data. According to Schreiner and Brown (1938), the nitrogen contents of the surface soils of the United States vary from 0.01 to 1% or higher. This means, then, that the range of organic matter content is approximately 0.2–20% and higher. At the higher ranges of organic matter the soils are either organic or have characteristics that approach those of an organic soil, which is usually defined as one in which the solid part consists predominantly of organic matter. Actually only a small percentage of the mineral soils of the United States contain more than 6% organic matter.

Variations by regions

A search of the literature reveals very little information on the average nitrogen or organic matter content of surface soils of various regions of the United States. This is not surprising because an average value has little meaning. In many regions an area as small as a county may have soils that vary at least 5-fold in their organic matter contents. In such a limited area, where variations in climate are negligible, soil texture, topography, drainage and vegetative cover are likely to be the controlling factors. These and other factors are discussed below in a section of this chapter. Even though average values are not too meaningful, it is of interest to know something of the general range of the nitrogen or organic matter contents of the main agricultural soils. Such a rough approximation has been presented by Schreiner and Brown (1938), and is reproduced here as Table 7.I.

The range of average nitrogen contents in the surface 6 inches of soil, according to Table 7.I, is 2,000 lb. in the red and yellow soils to 4,500 lb. in the chernozem and chernozem-like soils. Of course individual soils in each of these regions vary over much wider ranges. The western desert soils, not shown here, are extremely low in nitrogen.

The nitrogen analyses of soils shown in Table 7.I are for soils under natural conditions; after 50 years of cultivation decreases of 25–40% in organic matter in surface soils have been common, especially in the regions of the chernozem and chernozem-like soils, and in the chestnut soil region. In the prairie soils, and also in the forest soils of the eastern United States, such marked decreases in organic matter after being put under cultivation have occurred frequently, but not always. High fertilization and excellent farm management of these soils of the Humid region have frequently prevented such marked losses in organic matter, and actually reversed the trend, slightly at least, on many farms.

TABLE 7.I

AVERAGE NITROGEN CONTENT IN VARIOUS SOIL REGIONS OF THE UNITED STATES (from SCHREINER and BROWN, 1938)

Soil region	*Approximate area of region (acres)*	*Approximate nitrogen in surface 6 inches (%)*	*Average amount of nitrogen per acre to depth of 6 inches (lb)**	*Average nitrogen to depth of 40 inches (%)*	*Average amount of nitrogen per acre to depth of 40 inches (lb)*
Brown forest	180,000,000	0.05–0.20	2,500	0.05	6,700
Red and yellow	150,000,000	0.05–0.15	2,000	0.03	4,000
Prairie	113,000,000	0.10–0.25	3,500	0.12	16,000
Chernozem and chernozem-like	123,000,000	0.15–0.30	4,500	0.12	16,000
Chestnut	102,000,000	0.10–0.20	3,000	0.08	10,700
Brown	52,000,000	0.10–0.15	2,500	0.06	8,000

*2,000,000 lb of soil per acre.

TABLE 7.II

THE AVERAGE NITROGEN AND ORGANIC MATTER CONTENTS OF MINERAL SURFACE SOILS IN SEVERAL AREAS OF THE UNITED STATES (adapted from BUCKMAN and BRADY, 1969)

Soils	*% Nitrogen*		*% Organic matter*	
	range	*average*	*range*	*average*
240 West Virginia soils	0.044–0.54	0.147	0.74–15.1	2.88
15 Pennsylvania soils	–	–	1.70– 9.9	3.60
117 Kansas soils	0.017–0.27	0.170	0.11– 3.62	3.38
30 Nebraska soils	0.125–0.25	0.185	2.43– 5.29	3.83
9 Minnesota prairie soils	0.170–0.35	0.266	3.45– 7.41	5.15
21 Southern Great Plains soils	0.071–0.14	0.096	1.16– 2.16	1.55
21 Utah soils	0.088–0.26	0.146	1.54– 4.93	2.69

In Table 7.II are shown the averages and ranges of nitrogen and organic matter contents of mineral surface soils in various parts of the United States, as reported by Buckman and Brady (1969). For the most part these are analyses of soils that have been under cultivation for several years. These data emphasize the wide range of organic matter content in certain regions, especially in hilly regions where soils are not uniform and are subject at times to severe erosion.

Dean (1930) analyzed 223 unselected soil samples taken from various locations in the Hawaiian Islands where pineapples had been grown, or were to be grown shortly. Most of these unirrigated soils were sampled to a depth of 12 inches. The nitrogen contents varied over the range of about 0.1–0.6% with an average value of 0.31. The large majority of the soil nitrogen values fell in the range of 0.2–0.4%. Dean (1937) reported the analyses of 22 cultivated and 8 virgin Hawaiian soils, selected as representative of different rainfall areas. The average values for the 30 soils were: carbon, 6.6%; nitrogen, 0.49%; and carbon–nitrogen ratio, 13.5; if only the 22 cultivated soils are considered, the corresponding average values are 4.8, 0.37 and 12.8. These soils are surprisingly high in nitrogen and organic matter content, surpassing that of the chernozems in the continental United States.

Puerto Rican soils compare very favorably with soils of the Humid region of the United States in organic matter content, this being somewhat higher for the most part. The values, however, usually fall considerably below those given in the preceding paragraph for Hawaiian soils. Smith et al. (1951) reported organic matter values for typical Puerto Rican soils ranging between 0.74 and 5.87% for the surface 6 inches; the average was about 3.35%. Most of these soils, except in the uplands where erosion is a major factor, are considered deep soils. Under proper soil management the organic matter levels have usually been maintained and in some cases are now higher than they were in the virgin soils.

Variations with depth

All mineral soils decrease in organic matter content rapidly in going from the surface to lower depths, as is pointed out above. Broadbent (1953) has shown diagrammatically the distribution of organic matter in the profiles of several of the great soil groups. In general, the soils that are highest in organic matter in the plowed layer are usually richest in this at a depth of 2–3 ft. According to Broadbent's diagram the chernozem and gray-brown podzolic soils are the deepest soils, chestnut is intermediate, and the red podzolic and true podzols are the shallow soils. This arrangement is in general agreement with the data in Table 7.I. In this table the average amount of nitrogen per acre to a depth of 40 inches is shown to be only 4,000 lb. for the red and yellow soils in contrast to 16,000 lb. for the prairie, chernozem and chernozem-like soils; the others are intermediate in nitrogen contents.

FACTORS THAT DETERMINE ORGANIC MATTER CONTENT OF UNDISTURBED SOILS

The main processes involved in humus formation and decomposition are illustrated in Fig.6.1, drawn by Nikiforoff (1938). Even this rather involved diagram makes the various steps seem much less complicated than they are. In nature, numerous soil faunae, bacteria and fungi are constantly digesting and transforming the plant and animal residues into other forms, some simple and some complex. Each living form is in a sense a mass of enzymes that are ever active whenever there is a substrate present upon which it can feed, and when environmental conditions are favorable. Even when the plant and animal forms die, the transformations do not stop; the dead microorganisms and faunae then become the substrates on which other organisms feed.

The whole process of humus formation and decomposition is cyclic, but the cycle is not a closed one. Several elements, such as N, O, C, H, Ca, Mg, P, and S, and compounds containing them, may enter the cycle from outside sources including air, soil and water. These and other elements may also leave the cycle by escape to the air, by leaching, or by fixation in the mineral portion of the soil. In net effect, the losses from the cycle are usually greater than the gains from sources other than the original plant and animal residues for the obvious reason that decomposition processes consist chiefly in the reduction of large molecules to smaller ones, most of which can readily leave the cycle as gases or as soluble salts. The final product, humus, is the material that is left but it is not just inert residual material; it is that which remains after the breakdown products and residual materials have reacted with each other chemically, and undergone considerable polymerization to form a product that is very different from both the source materials and their degradation products. It is very resistant to further biological attack and its weight may constitute only 10, 5, or even 1% of the dry weight of the original undecomposed organic substances that gained entrance to the soil.

The main factors that determine the rate and extent of the formation and oxidation of humus in soils under natural conditions, uninfluenced by the activities of man, are outlined and discussed below.

Amount and type of vegetation

The humus content of a soil is dependent primarily on the quantity of plant (and animal) material per unit area that reaches the soil and the rate of its decomposition. Although this obvious statement seems to reduce the matter of humus accumulation to very simple terms, actually it is not so simple. Many factors influence both the type and quantity of vegetation that is available for humus formation, and, likewise, the activities of the biological and chemical agencies that bring about decay. The result is that the humus content of a soil does not necessarily bear a close relationship either to the quantity of residues returned to the soil or to the rate of their decomposition. Furthermore, even after decomposition has proceeded to the humus stage, all of it may not remain in the soil. Wind and water erosion, and leaching, may transport some of the humus to distant locations. Where soils are left undisturbed these losses are kept at a minimum.

The quantity of vegetable material returned to a soil yearly may vary from near zero in arid and arctic regions to many tons of dry matter per acre under ideal tropical conditions where growth may continue throughout the year. The main factors involved are the type of vegetation, temperature, moisture, soil fertility and the many soil characteristics that determine its suitability for the growth of the kinds of plants native to the area. Under natural conditions both the roots and tops of the vegetation serve as sources of humus although there may be some losses through animal grazing, by fires and by wind transport. This means almost complete conservation of the humus sources, and under favorable soil and climatic conditions commonly leads to a high level of accumulation before an equilibrium is reached where humus formation and humus degradation are equalized.

The characteristics of the plant materials that act as humus sources also play an important part in determining the amount of humus that accumulates in soils. Reference has already been made to the accumulation of slowly decomposing coniferous residues on the soil surface, followed by the leaching of the organic acids downward through the soil profile. This leads to the formation of stratified podzols which are not high in organic matter. In contrast are the soils formed under deciduous forests, where more readily decomposable and more nutritious leaf and twig residues are eaten by earthworms and insects and are rapidly mixed with the soil to a depth of a foot or more. Microorganisms help to convert this into humus, and since the typical podzol leaching process is much less in evidence and calcium is more abundant, the result is a fairly marked accumulation of organic matter to a fair depth. Still more favorable to the build-up of soil humus is the grassland type of vegetation, where the quantity of plant material returned to the soil is rather large, where leaching is less in evidence, and where limited moisture and moderate temperature tend to retard the rate of decomposition.

Soil fauna and flora

The activities of the soil fauna and flora in the humification process are discussed in previous chapters. It is these living organisms that are almost wholly responsible for plant decomposition since purely chemical reactions apart from enzymatic transformations are very minor except in the final stages of humus formation. Although the animal population, especially the earthworms, is often very important in the incorporation of the plant residues into the soil, and in the mixing process, it is the bacteria and fungi that play the major role. The decomposition of plant and animal debris can proceed in the complete absence of all animals, but humus formation in the absence of microflora does not occur. Working cooperatively, as occurs normally in nature, the process is speeded up. Since both kinds of organisms bring about the changes it is obvious that their numbers are important, but large populations do not necessarily mean more humus formation from a given amount of organic debris; sometimes the reverse is true because biological activities involve hydrolysis and oxidation, which are degradation processes.

Where fungi predominate, the loss of carbon as CO_2 is likely to be less per unit of original carbon than that lost if bacteria predominate, because the former organisms convert more of the carbon into their own cell structure. Bacteria thrive best on a near-neutral substrate that is rather proteinaceous; fungi will also grow luxuriantly on such a medium, but can also tolerate comparatively high acidity and grow actively on very nitrogen-deficient plant materials, high in cellulose. Where moisture is too deficient for either bacteria or fungi to make much growth on carbonaceous materials, it is common to find actinomycetes as the dominant microorganisms.

Climate

The importance of climate in the determination of the quantity of organic matter in soils has been studied by a number of persons, especially Jenny and associates; Dean; and Smith, Samuels and Cernuda. Although there is general agreement that climate is of major importance there is still considerable uncertainty as to why data from different regions do not always fall into the expected pattern.

Jenny (1930) studied the soils of the central United States and found that at constant moisture content the nitrogen and organic matter contents of both grassland and timbered soils increase exponentially as the temperature decreases. For each fall of 10°C in annual temperature the average nitrogen and organic matter content of soils increased 2 to 3 times. The carbon–nitrogen ratio of the organic matter also increased as the temperature decreased. Jenny observed, further, that at constant temperature the nitrogen and organic matter contents of soils of the central United States increase logarithmically with increase in moisture. In his opinion, the order of importance of the main soil-forming factors (apart from cultivation) on the nitrogen level of loamy soils within the United States as a whole is: climate > vegetation > topography and parent material > age.

Jenny et al. (1948, 1949) studied the soils of Colombia, South America and Costa Rica, and found considerable agreement with results reported earlier for soils of the United States except that under similar temperature and moisture conditions Colombia soils have much higher nitrogen and organic matter contents than those of North America. In the hot and humid areas of Colombia many light-colored soils were found to be rich in nitrogen and organic matter. In explanation of the high values for tropical forest soils Jenny (1950) points out that the litter fall is high, and postulates that the favorable climatic conditions, together with a high rate of fixation of nitrogen by legumes, are the primary cause of luxuriant vegetation. He observed that the surface forest litter decomposes rapidly and apparently a considerable part of the products leach into the mineral soil where decomposition is slow and humus can accumulate to a high level. It is true that organic matter decomposes at a slower rate in the presence of clay than in sand or no mineral matter but this explanation is scarcely adequate to explain the comparatively high levels of organic matter in tropical soils.

In studies of the effect of climate on nitrogen and organic matter in Indian soils Jenny and Raychaudhuri (1960) observed temperature and moisture effects similar to those found for soils of the United States, except that the organic matter levels under comparable conditions were higher in Indian soils. These levels were not as high, however, as those in Central America and in the equatorial regions of South America. They found that soils in the drier climates and those that had been in cultivation for many years had lost 60–70% of their organic matter. In spite of this fact they concluded that the low level of organic matter in many Indian soils is caused primarily by environmental conditions, and only secondarily by cultural practices.

Dean (1930) reported that Hawaiian soils are rich in nitrogen as compared with those in the southern states of the United States, and that the carbon–nitrogen ratio of the organic matter becomes narrower with increasing mean annual temperature.

In other studies on the effect of climate on Hawaiian soils, Dean (1937) found that the carbon and nitrogen contents of soils increase with increasing rainfall and elevation. The carbon–nitrogen ratio of soils increased with increasing rainfall.

Smith et al. (1951) pointed out that organic matter and nitrogen are relatively high in Puerto Rican soils over a wide range of rainfall conditions and are at least as high as in many of the best soils of temperate regions. Two to three percent organic matter to a depth of 12 inches is not uncommon. They state that "the predominant factor in the organic matter balance is believed to be climatic or combined climatic and biotic. The frost-free boundary is suggested as a climatic limit for the original concept of Jenny regarding the progressive decline of soil organic matter with increasing average temperature. It appears logical that the absence of killing frost favors the building of organic material by green plants much more than it favors destructive microbiological activity within soil. By this logic, minimum soil organic matter contents under humid conditions would be expected in areas with frost but with relatively warm, long winters during which microbiological activity and soil leaching would continue but green plants would be dormant. This approximates the conditions under which Jenny has shown his minimum soil organic matter values for the United States." I am in full agreement with Broadbent (1953) when he states that this statement of Smith et al. "appears to be the most plausible explanation so far advanced to account for organic matter accumulation in tropical soils." When most of the vegetation dies, these dead tissues are subject to rapid decomposition; when they remain alive from year to year decomposition is limited largely to sloughed-off root cells, leaves that drop, and parts of stems that from time to time die. Continuous growth compensates for these partial losses and the organic matter level thereby remains at a comparatively high level.

Parent material and topography

Soil texture is an extremely important factor in the determination of the humus content of soils. Under similar climatic conditions the quantity present may commonly be 2–4 times as great in a fine-textured clay soil as in a very sandy soil. Some of this difference is attributable to better aeration and increased oxidation in the coarse-textured soil, but the main difference is due to: (1) the formation of organic–inorganic complexes; (2) the sorption of the organic matter on the clay particles and fixation in the crystal lattices of the clays; and (3) the formation of metal–organic compounds, such as Ca, Fe and Al humates. Those clays having the 2:1 type structure with high absorptive capacities and with expanding crystal lattices that allow organic molecules to be trapped, are very effective in the retention of organic compounds. These organic–inorganic products are largely or wholly colloidal in nature and hence largely absent from sandy soils. It has been shown repeatedly that the nature of the organic fraction is much the same in coarse- and fine-textured soils, and that the percentage of organic carbon in the clay fraction of both types of soil is fairly constant under similar climatic conditions.

Soil reaction, which is affected by mineral composition, climate, and agricultural practices is also of at least some appreciable importance under some conditions in its effect on soil organic matter levels. Very low pH values may curtail plant growth and hence the quantity of organic matter that gains entrance to the soil. On the other hand, low pH values may retard the rate of decomposition and also favor the growth of fungi over bacteria, and fungi are more conserving of organic carbon. Acid soils are deficient in calcium, which is known to help hold carbon through the formation of calcium humates. Since at any soil reaction there are factors at work in opposite directions the effect of pH on organic matter levels is often not very great.

Topography is an important factor in its effect on the organic matter level of a soil. It affects temperature (or microclimate), infiltration, total loss of water through runoff and evapotranspiration, depth of water table, and erosion which tends to limit soil depth. Topography is commonly described in terms of slope gradient, length, direction and curvature. Many of these factors influence the type and amount of vegetation found at any location, the rate of humification, and losses of carbon sources through water and wind movement. Where mountains are involved the elevation is very important and, as already stated, the organic matter content of such soils commonly increases with elevation.

In poorly-drained soils, or those that are naturally quite moist for much of the time, the organic matter contents are likely to be above average provided the soils are not unfavorable for a good vegetative cover. Excess moisture means partially anaerobic conditions for much of the time and hence retarded decomposition of the carbon sources.

Time

Organic matter accumulation, starting with a humus-free soil, is a function of time. Stevenson (1965) has presented an excellent discussion of the subject and pointed out some of the factors of major importance in the process. He states that in general the rate of nitrogen accumulation, and hence of organic matter accumulation, is rapid during the first few years, then slowly diminishes, and reaches equilibrium after 110–1500 years.

The time required is obviously dependent upon almost all of the factors that affect plant growth and also all that affect the decomposition of these sources of humus. The most important mineral element involved is nitrogen, since this is the main constituent of humus that is not readily available from the air or soil. Since under natural conditions most of the nitrogen must be added to the soil by means of nitrogen-fixing organisms, the rate of organic matter accumulation during the first few years is often directly related to the quantity of nitrogen supplied by the symbiotic and nonsymbiotic nitrogen fixers.

EFFECT OF AGRICULTURAL PRACTICES

The organic matter content of a soil is often markedly affected by the treatment that the soil receives at the hand of the agriculturalist who is responsible for the crop and soil management practices applied to it. Since most of these practices are discussed in later chapters, the remarks at this point will be limited largely to a broad review of the subject.

Plowing and cultivation

It is the moldboard plow and the various systems of cultivation that keep the soil bare for a considerable portion of the year that are primarily responsible for marked decreases in soil organic matter following the breaking of virgin land. The conditions responsible for the steady state of the soil organic matter, built up over centuries to the maximum level possible under the prevailing climatic and soil conditions, are suddenly drastically changed. Destructive oxidation processes now greatly outweigh the constructive ones and

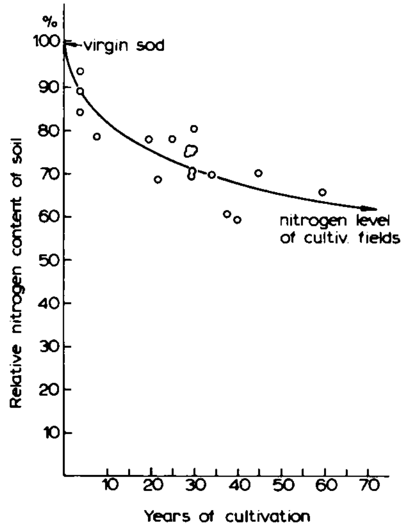

Fig.7.1. Decline of soil nitrogen with length of cultivation periods under average farming practices in the Middle West. (From Jenny, 1933.)

under many, or most, conditions the organic matter level decreases rather markedly during the following 25 or more years. The decrease can be partially prevented, as is pointed out below, if the best farm practices are followed, but rarely have such operations been applied to newly-plowed virgin soils. In practice in the United States, virgin soils have usually been mined for their nutrients until such time as decreasing yields made necessary the adoption of better farm practices.

The organic matter level is usually higher in undisturbed soils because all native vegetation remains on the soil, erosion is negligible, and oxidation is at a minimum. Under cultivation much of the vegetation produced is removed, water and wind erosion are tremendously accelerated, and frequent cultivations favor the destructive processes. The degrading effects are likely to be most in evidence in the Temperate Zone where the native vegetation was grass sod, and rainfall was adequate for good growth.

The rate and extent of the decrease in nitrogen (and also organic matter) following the breaking up of Missouri land is shown in Fig.7.1. This figure is taken from the publication of Jenny (1933). It will be noted that about 25% of the nitrogen had been lost from the soil in 20 years and 35% in 60 years. Similar data, reported by Haas et al. (1957) and Hobbs and Brown (1957), for locations in the dryland area of Kansas, are shown in Fig.7.2. These data are representative of much other data obtained in the same region and extending north into Canada. Few regional data of this type are available for the eastern podzols but the decreases in organic matter due to cultivation have probably been less drastic, mostly because the carbon content of the virgin soils was not high.

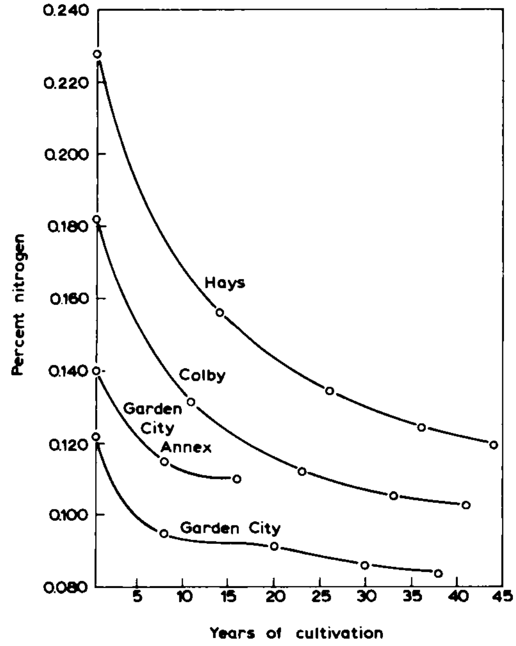

Fig.7.2. Effect of cultivation on nitrogen content of surface soils of Hays, Colby, and Garden City, Kansas. (From Hobbs and Brown, 1957.)

Jenny and Raychaudhuri (1960), as mentioned above, observed a loss of 60–70% of the organic matter from Indian dryland soils that had been long under cultivation. Doubtless these soils that received inadequate fertilizer and water produced small crops, most of which, except the roots, was removed yearly. These conditions are extreme and would be expected to lead to maximum humus depletion.

Erosion control

Erosion, if not controlled, is one of the major reasons for marked decreases in organic matter in soils. In many regions of the United States, especially in the southeastern states, it is not uncommon to find soils that have lost essentially all of their original topsoil since they were first put under cultivation. These soils formed under forests were never deep soils. In addition to direct removal of the soil mass to lower levels is the fact that both water and wind have a selective action. Neal (1944) states that the nitrogen, and hence organic matter, in eroded material may be as much as five times higher than in the soil that remains. Wind also tends to remove the lighter material first. The effects of erosion and means of control are discussed by Stallings (1957), and in a more limited way in Chapter 27 of this book.

Cropping systems

The harmful effect of continuous clean cultivation on soil organic matter can be greatly reduced by the adoption of a cropping system that reduces the number of cultivations and keeps the soil protected by vegetation as much of the time as possible. Allison and Sterling (1949) presented data showing that in field experiments at Mandan, North Dakota, the loss of nitrogen during the first 33 years of cropping was 34% for continuous corn or for corn alternated with summer fallow. The loss with continuous small grains was 14%, and for small grains alternated with fallow 26%. Where grass sods are maintained, even in regions of heavy rainfall, there is little if any loss of nitrogen or organic matter. Grass culture represents the most ideal soil conservation practice but its use is necessarily limited chiefly to livestock farming. Certainly rotations that include sod crops should be used wherever feasible.

Fertilization and liming

Fertilizers applied as a supplement to proper cropping systems can go far toward maintaining soil organic matter. This is obvious since they increase plant growth, and this means more crop residues including roots that will be returned to the soil. It is especially important that adequate nitrogen be applied since this element constitutes about a twentieth of the weight of soil organic matter. The addition of the necessary nutrients, including lime if needed, can go far toward offsetting the degrading effect of cultivation on soil organic matter, not by stopping the oxidation but by increasing yields and thereby supplying more carbon-containing compounds to replace those being oxidized.

Disposal of crops and their residues

The smaller the crop and the more completely it is removed from the soil, the more rapidly the soil humus will decrease. Conversely, the larger the crop and the more of it that is returned to the soil the higher the level of organic matter that can be maintained. But this level will usually be considerably below that of the original virgin soil if the soil is plowed and cultivated at frequent intervals. Nature will establish the humus level at whatever point the synthetic and oxidative processes balance. This level need not be as high as that of virgin soils but only high enough to insure bumper crops.

PRESENT STATUS OF ORGANIC MATTER IN ARABLE SOILS

In the United States

From the above discussion it is obvious that no general statements regarding soil organic matter levels can be made that apply to all soils, but it is possible to generalize on many of our main agricultural soils. When this is done the outlook as a whole is very favorable; in most of our well-fertilized arable soils the organic matter level is either remaining at constant level or actually increasing at a slow but significant rate. Now that soils have been in use for 50–300 years it is obvious that even if poorly treated and unfertilized they are not losing much organic matter. As pointed out above, the mining process is usually nearly completed after 50 years and by that time a new equilibrium has been reached or closely approached.

The revolution that has occurred in agriculture during the past 20–40 years has had a corresponding impact on soil fertility and soil carbon content. Heavy fertilization, together with the general adoption of improved farm management practices have doubled the yields of many of our crops. Accompanying this has necessarily been a doubling or tripling of the amount of crop residues produced and returned to the soil. Under these conditions of intensive and well-managed farming the maintenance of organic matter at a satisfactory level usually does not present major problems except for special soil types and a few crops. This level has also been favored by the emphasis placed on minimum tillage (see Chapter 24). Sod crops may still need to be included in most rotations for various reasons, especially for erosion control, but they are certainly not as essential now as they were when soils were being mined constantly. For example, ways have been developed that allow for continuous corn production on some soils without depletion of soil organic matter (Melsted, 1954 a,b) but such methods are now used only to a limited extent.

The increases in soil organic matter that have been realized have been largely limited to the Humid region, or where irrigation is practiced, because obviously if water is the limiting factor in plant growth there is an inadequate supply of crop residues for increases in soil organic matter levels. Under intensive farming conditions in the Humid region considerable changes have also occurred in the location of the organic matter in the soil profile. The stratification that was characteristic of podzols has been largely replaced by a better distribution of the organic matter. This is a natural result of plowing and elimination of the surface layer of acid leaf litter through which percolation occurs under forest conditions. Many of these podzols now closely resemble soils formed under grass sods.

In Europe

Conditions in Europe, so far as soil organic matter maintenance is concerned, are for the most part, excellent. In general, European agriculture passed through the mining stage, the livestock stage, and now the intensive fertilizer stage much as has occurred in the United States, but at an earlier time because Europe is an older part of the world. Europe has also been favored by a better climate in some respects, especially the absence of torrential rains that produce so much havoc on freshly cultivated soils. Jacks (1963) gives a fairly complete and excellent review of the history of agricultural developments over the centuries in Western Europe, including the British Isles. A more complete and extensive treatment of the subject is found in the work edited by Clapham and Power (1941).

A paragraph from the book by Nye and Greenland (1960) gives a concise summary of the subject that is adequate for present purposes. They state that "The highly productive agriculture of present day Europe has only slowly evolved from shifting cultivation. When irregular cropping settled down to the open field system, fertility was maintained at a low level by a year of fallow after one or two years of crops, and by the limited amount of manure that reached the fields from animals grazing the common land beyond. The fallow was only finally abandoned with the introduction of root crops as winter fodder, leading to more cattle and more manure. Today fertility is maintained by a reversion to a fallow system – though with greatly improved fallows – called ley farming, by imports of feeding stuffs, and above all by inorganic fertilizers."

In the Tropics

The unexpectedly high levels of organic matter found in many soils in Colombia, South America, Costa Rica, Puerto Rico, Hawaii, and even in some Indian soils, is pointed out above and the probable reasons given. There is little quantitative information on what happens to these soils when cultivated for years but it seems safe to conclude that they respond very much like soils elsewhere. At least, this is true in Puerto Rico, as Smith et al. (1951) point out. Where erosion is controlled, they state that the comparatively high organic matter levels can be maintained with continuous sugar cane, coffee, and close-growing forage crops. They emphasize the great importance of legumes, especially kudzu, in the maintenance of high organic levels and in the rapid build-up of organic matter in exposed subsoils.

Conditions in the soils of Africa and elsewhere where a shifting type of primitive agriculture is followed, or on the soils of the savannas, are discussed in Chapter 20. Obviously the organic matter levels here, where conditions have changed little over the centuries, tend to remain constant.

REFERENCES

Allison, F.E. and Sterling, L.D., 1949. *Soil Sci.*, 67: 239–252.

Broadbent, F.E., 1953. *Adv. Agron.*, 5: 153–183.

Buckman, H.O. and Brady, N.C., 1969. *The Nature and Properties of Soils.* Macmillan, New York, N.Y., 653 pp.

Clapham, J.H. and Power, E., 1941. *The Cambridge Economic History of Europe from the Decline of the Roman Empire.* Cambridge Univ. Press, London, 650 pp.

Dean, A.L., 1930. *Soil Sci.*, 30: 439–442.

Dean, L.A., 1937. *Proc. Soil Sci. Soc. Am.*, 2: 455–459.

Fuller, W.H., McAlister, D.F. and Metcalfe, D.S., 1960. *Adv. Agron.*, 12: 197–227.

Haas, H.J., Evans, C.E. and Miles, E.F., 1957. *U.S. Dep. Agric., Tech. Bull.*, 1164: 1–111.

Hobbs, J.A. and Brown, P.L., 1957. *Agron. J.*, 49: 257–260.

Jacks, G.V., 1963. *Soils Fert.*, 26: 147–150.

Jenny, H., 1930. *Mo. Agric. Exper. Stn. Res. Bull.*, 152: 1–66.

Jenny, H., 1933. *Mo. Agric. Exper. Stn. Bull.*, 324: 1–10

Jenny, H., 1950. *Soil Sci.*, 69: 63–69.

Jenny, H. and Raychaudhuri, S.P., 1960. *Effect of Climate and Cultivation on Nitrogen and Organic Matter Reserves in Indian Soils.* Indian Council of Agricultural Research, New Delhi, 126 pp.

Jenny, H., Bingham, F. and Padilla-Saravia, B., 1948. *Soil Sci.*, 66: 173–186.

Jenny, H., Gessel, S.P. and Bingham, F.T., 1949. *Soil Sci.*, 68: 419–432.

Melsted, S.W., 1954a. *Adv. Agron.*, 6: 121–142.

Melsted, S.W., 1954b. *Proc. Soil Microbiol. Conf., Purdue Univ., Lafayette, Ind.*, pp. 1–13.

Muir, A., 1961. *Adv. Agron.*, 13: 1–56.

Neal, O.R., 1944. *J. Am. Soc. Agron.*, 36: 601–607.

Nikiforoff, C.C., 1938. In: *Soils and Men – The Yearbook of Agriculture, 1938.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., pp. 929–939.

Nye, P.N. and Greenland, D.J., 1960. *The Soil under Shifting Cultivation. Commonwealth Bur. Soils, Tech. Commun.*, 51, 156 pp.

Schreiner, O. and Brown, B.E., 1938. In: *Soils and Men – The Yearbook of Agriculture, 1938.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., pp. 361–376.

Sivarajasingham, S., Alexander, L.T., Cady, J.G. and Cline, M.G., 1962. *Adv. Agron.*, 14: 1–60.

Smith, R.M., Samuels, G. and Cernuda, C.F., 1951. *Soil Sci.*, 72: 409–428.

Stallings, J.H., 1957. *Soil Conservation.* Prentice-Hall, Englewood Cliffs, N.J., 575 pp.

Stevenson, F.J., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 1–42.

Viro, P.J., 1963. *Soil Sci.*, 45: 24–30.

Chapter 8

THE NATURE AND COMPOSITION OF SOIL ORGANIC MATTER

INTRODUCTION

In a discussion of the general nature of soil organic matter it is well to point out that there are wide variations in the characteristics of soil organic matter depending on the vegetation, climate and biological conditions under which the material accumulates. This statement applies particularly to the total organic matter that includes a large amount of plant and animal residues that have not yet been thoroughly humified; as decay proceeds, the humic substances formed tend to become more and more alike regardless of the nature of the original humus sources. Climatic conditions under which decay occurs are important in determining the nature of the final product.

ORGANIC MATTER IN VARIOUS SOIL ENVIRONMENTS

The comparatively marked initial variations in the nature of soil organic matter taken from different locations are related closely to the vegetative cover and climatic conditions that prevailed for hundreds of years prior to their being used for the growing of cultivated crops. These conditions as commonly found in virgin forest, grassland, prairie and desert soils are broadly outlined in Chapter 7 and need not be repeated here.

When virgin soils are brought under cultivation there is likely to be a marked change in their characteristics. And the less suited the soil was originally for crop production, the greater the changes that must be brought about by man. If the soil is very acid, it must receive Ca, Mg, K and very likely P and N, as well as minor elements. Such additions are especially needed on the more acid podzols and lateritic soils that have been subjected to drastic leaching over the years. The grassland soils and brown earths are probably already neutral or even slightly alkaline, and are quite productive with little or no fertilization.

Aside from the chemical changes that man makes, there are marked physical and biological changes. The removal of a forest, for example, is alone a drastic change since this eliminates podzolization. The substitution of cultivation for native grass is also a marked change but probably less so than deforestation. The removal of native vegetation, whatever it may be, also changes the animal life in soils. The animals present originally are the ones that thrive in the prevailing environment, especially the plant cover and the food that it supplies. When this is removed, most of the fauna die and other species may take their place but only to a limited extent.

Cultivation hastens decay processes and the crop residues are rapidly converted into carbon dioxide and humus. Only a minimum of the original cellulose, hemicellulose and protein remain. Microbial residues replace them to a limited extent.

Bog soils, commonly described as peat or muck, are discussed in some detail in Chapters 29 and 30, but need to be mentioned here because most of the chemical studies of humus have been made on humus extracted from these soils rather than from mineral soils. This is in some respects unfortunate because humus from the two sources is not exactly the same, although similar. Bog humus is used in such studies chiefly for practical reasons; it is more readily obtained in quantity from peat or muck soils and contains much less clay. In mineral soils much of the 1–5% humus usually present is there in stable combinations with the inorganic portion of the soil and cannot be removed except by very drastic chemical treatments that may markedly decompose or otherwise change the organic matter.

In its natural state soil organic matter may contain the following materials: (1) at least small amounts of most any of the constituents that were present in added plant and animal tissues; (2) the products formed biologically and chemically during decomposition; (3) living and dead microbial cells; (4) the degradation of soil organisms; and (5) the interaction products of any or all of these substances. To further complicate the picture is the fact that these substances, many of them colloidal in nature, commonly occur in intimate mixture with inorganic colloids and in the clay lattices of the minerals.

CHEMICAL NATURE OF SOIL ORGANIC MATTER

Some early concepts of humus and its formation

Much effort has been exerted during the past 50–75 years in attempts to determine the chemical nature of humus and its mode of formation. Waksman (1938) has summarized the earlier studies adequately, but it does seem advisable to make specific reference to the paper by Schreiner and Dawson (1927) and to Waksman's proximate analysis method.

Views of Schreiner and Dawson

Special reference is made to the paper by Schreiner and Dawson because the ideas presented by them were in many respects far in advance of the thinking at that time. In fact, they are in surprisingly close agreement with our present concepts. Their paper incorporates some of the ideas of earlier workers together with modification based on their own laboratory findings.

These authors pointed out that under laboratory conditions, organic chemists have observed that a number of reactions yield a variety of artificial humus, humic acid or humin substances that are more or less similar in their physical and chemical properties to each other and to naturally occurring substances. In most studies these by-products of the laboratory and of technical processes were unwelcome and received little study. They are of great interest, however, in connection with the chemistry of soil humus formation. Schreiner and Dawson state that the variety of reactions that yield similar products suggests that "the naturally occurring substances are rarely homogenous products of any one type of reaction or any one group of parent substances, but that they represent accumulations of the more resistant end-products of a variety of reactions taking place under natural conditions, either directly or indirectly through biological processes." This concept emphasizes the difficulty in the determination of mechanisms of humus formation by the study of the end-products. These authors considered that the better method is to study under controlled conditions the various reactions that yield humus or humus-like products. They list three types of such reactions.

First, humus-like substances may be formed by the action of mineral acids upon hexose sugars, as has long been known. More complex carbohydrates are first broken down into their monose derivatives. After hydrolysis the transition products may undergo rapid condensation with a piling up of molecular weight to form insoluble "humins". Attempts to identify these compounds or fractions of these mixtures were not successful.

Second, humus-like substances may also be formed from phenolic compounds and quinones by oxidation. Examples are oxidation of alkaline solutions of pyrogallol, hydroquinone, catechol, etc. The process of condensation proceeds with great rapidity, leading to a complex mixture of products of varying degrees of condensation and solubility, and varying empirical composition. They state that "ring rupture between the two adjacent quinone carbons and immediate re-condensation of the resulting open-chain intermediate, through its highly reactive terminal groups", may be involved.

A third type of reaction leading to humus-like substances involves the reaction of amino-acids and other amino compounds with carbohydrates or aldehydes. The nitrogen in the final products is tenaciously retained as a part of the complex.

Schreiner and Dawson state that there are many other reactions that lead to amorphous or resinous condensation products similar to humus substances, but the three cited above are the ones that could involve plant constituents. Consideration must also be given to lignin which on decomposition yields compounds of phenolic and furan aldehyde character; it may contribute to humus formation through any of the processes mentioned above. The microorganism is considered as "an intermediate in the general process, the remains of its structures and its metabolic products constituting stages in the series of reactions involved in the 'humification' process." They consider that the processes in soil are not much different from those in the laboratory except very much slower. However, in the soil we encounter "the effects of high surface activity of soil particles, inorganic catalysts and highly potent biological factors", which, they state, are capable of leading to the same end-products. The soil humus complex is considered as "representing an accumulation of the more resistant products, in varying degrees of chemical condensation, of a number of reactions, as illustrated, involving a wide variety of parent substances." Even though resistance of the humus complex is emphasized, they consider that the complex "involves no static condition, but a dynamic equilibrium constantly shifting with the supply of raw material, alteration of the biological population of the soil and alteration in the physical or chemical conditions imposed by cultural methods or fertilizer application."

The proximate analysis method

One of the interesting early developments in the study of soil organic matter was the extensive use of the proximate method of analysis (Waksman and Stevens, 1928a,b; 1929a,b; 1930a,b; Waksman, 1938). This method follows closely the system used in plant analysis and enables the analyst to determine, at least in a general way, the major changes that occur as plant materials undergo decomposition. Waksman and Stevens used the method primarily in the study of the chemical nature of peat, and accounted for about 90% of the organic substances present in it. By the use of this method they were able to show marked differences between different kinds of peats and thus gained considerable information on the decomposition processes that had taken place during peat formation. For example, in lowmoor peat, decomposition had proceeded to the point where cellulose was absent and hemicellulose was present in only limited amounts. In contrast, considerable quantities of both cellulose and hemicellulose remained in highmoor peat, showing that much less decomposition had taken place. Ether-soluble substances had accumulated in highmoor peat but not in the lowmoor peat. These results emphasize very strikingly how the stage of decomposition of plant substances affects the composition and characteristics of the residual organic matter. In the final stages of decay, humus from different sources may be similar but in the earlier stages of decomposition the variations can be quite wide.

When Waksman and Stevens (1930a,b) applied the proximate analysis method to soil organic matter they found that it is made up largely of two groups of compounds, the lignin-like complexes and the nitrogenous complexes or compounds which they believed to be primarily proteins. In addition, some fats, waxes and resinous substances were present, and also some hemicellulose and small amounts of cellulose-like substances. These findings led Waksman (1938) to conclude that humus consists largely of complexes of lignin and protein or modified forms of these substances. A series of ligno-protein complexes was prepared that behaved similarly to natural humus from soils, peat and composts. He emphasized that the nature of the "humus-nucleus" and of humus as a whole is not the same under all conditions since lignins and proteins differ, the microbial populations differ, the composition of the plant residues undergoing decomposition varies, and the environmental conditions are never the same.

Although this ligno-protein concept of humus represented an advancement in the study of the nature of humus and stimulated research, we now know that there is little basis for believing that this complex actually exists in appreciable amounts in soil. In fact, lignin undergoes such marked changes that after thorough decomposition it can no longer be considered to be lignin. The lignin residues exist in complexes but more likely as fused ring structures. Protein has not been isolated from soils (Bremner, 1965) and if any is present it is likely to be of microbial origin and present in the portion of the organic matter that is still considered as biologically active. It is generally believed that it is the protein degradation products, amino acids, and the lignin residues that combine to form the resistant complexes found in thoroughly humified organic matter. This is in agreement with Schreiner and Dawson (1927) and with the views of others mentioned in a later section of this chapter.

Non-humic and humic substances

The variability of soil organic matter with stage of decomposition leads to difficulties in the matter of defining or describing the material or fractions of it. The common practice is to divide soil organic matter into non-humic and humic substances.

The non-humic substances are the compounds that are the chief constituents of higher plants, animals and microorganisms. These include proteins, carbohydrates, lignins, fats, waxes, resins, pigments, tannins and certain compounds of low molecular weight. These compounds constitute the energy-supplying food of soil microorganisms. The portions not readily utilized by them, plus portions of the attacking microorganisms themselves, remain in the soil and serve as source materials for humus formation. They do not remain indefinitely in their original form; some of them undergo polymerization, or interactions to form compounds or complexes of large molecular size, which may undergo further decomposition but only at extremely slow rates.

Humic substances are usually described as acidic, relatively high-molecular weight substances, that have a yellow, brown, or black color. Van Dijk (1966) refers to humus as a globular, polydisperse, irregular polycondensate. Humic acids are produced in soils, compost piles, and elsewhere primarily through biological action followed, or accompanied, by chemical reactions. Felbeck Jr. (1965a) states that it has been the general belief that these substances are rather homogeneous but differ considerably in molecular weight. Three classes of substances are generally recognized, namely, fulvic acid, humic acid and humin. Fulvic acid, which is alkali- and acid-soluble, has the lowest molecular weight; humic acid is alkali-soluble and acid-insoluble and of intermediate molecular weight; and humin which is insoluble in both acids and alkalis, except under unusually extreme conditions, has the highest molecular weight. There is now evidence indicating that fulvic acid may differ chemically from humic acid and humin (Felbeck Jr., 1965a). The molecular weights of these three types of humic substances are believed to fall in the range of 2,000–400,000, but there are no accurate quantitative data for the more insoluble fractions.

Dubach and Mehta (1963) define humic substances as a series of predominantly aromatic-phenolic polymers, whose acidity is mainly due to carboxyl groups, and which are free of carbohydrates and probably of nitrogen. They state that the presence of quinonic structures cannot be confirmed or excluded. They are of the opinion that there are ether linkages between the aromatic monomers, but humic substances are too nonhomogeneous to justify an attempt to write a structural formula for them, as was done in the past. The humic substances constitute over 50% of the organic matter of mineral soils. At the present time few workers would have any doubt that these substances contain nitrogen.

There is no sharp line of demarcation between non-humic and humic substances. Both types of substances are present at all times in all soils and there is constant change of the former into the latter, even if slowly. A sugar may be decomposed largely into CO_2 and H_2O, but a variable portion of even such a simple compound is converted into numerous microbial cell substances, and thus becomes a part of humus. Proteins may be decomposed largely into amino acids and ammonia but both of these substances are ideal foods for microorganisms, and may also undergo various chemical reactions. Even a comparatively inert material such as lignin may be demethoxylated and degraded to varying degrees. At the same time, lignin-like compounds are being synthesized by many species of fungi (Pinck and Allison, 1944) from sugars, cellulose and other utilizable carbon sources that may be present. Obviously, any classification of the mass of materials continually being produced in such a dynamic environment cannot be very exact, but does serve an essential purpose.

The proportion of humic substances that is of microbial origin is not known but there are good reasons for believing that it may amount to most of the total. The main reason for this statement is that most plant and animal substances other than lignin are decomposed rather rapidly and almost completely. Lignin also undergoes decomposition but more slowly. The degradation products of plant and microbial tissues serve as building units in the construction of high molecular complexes. Unmodified residual materials of plant origin play a very minor role in complex formation.

Major chemical constituents of soil organic matter

Our knowledge of the chemical nature of soil organic matter is very unsatisfactory. This is obvious from what has already been said. It is also obvious that the difficulties facing the investigator in this field are almost overwhelming because of the heterogeneity, variability and complexity of humus. Waksman (1936) referred to humus as a state of matter, rather than as a specific substance.

In the process of trying to find out all that we can about the chemical nature of soil organic matter, or humus, various means of nibbling off a small section of the complex are commonly used, and its composition then determined, but this leaves the big question of whether this small segment actually existed as such in the original material. If so, how was it arranged and how essential a part of the whole was it? Could it be merely an artifact?

In the present discussion only the general nature of soil organic matter and some of the more important established facts regarding its chemical composition will be presented. The mass of work that deals with methods, model compounds, most chemical analyses, and interpretation of the bits of information gathered by various procedures, cannot be considered here in detail. Many excellent review articles are available that supply this information. As already stated, the older literature is covered adequately by the classical book on humus by Waksman (1938). An earlier book by Waksman (1932) considers the role that microorganisms play in soil. Some of the recent reviews are the following: Dawson (1950, 1956), Bremner (1951, 1954, 1965), Broadbent (1953, 1955), Thiele and Kettner (1953), Fraser (1955), Scheffer and Ulrich (1960), Kononova (1961), Russell (1961), Dubach and Mehta (1963), Mortensen (1963), Whitehead and Tinsley (1963), Mortensen and Himes (1964), Felbeck Jr. (1965a), Flaig (1966) and Hurst and

Burges (1967). In a later section of this chapter the biochemistry of humus formation and proposed hypotheses on the structure of humus are discussed.

Nitrogenous substances

Ninety-five percent or more of the nitrogen in surface soils is usually present in organic form. The remainder is present as ammonia, nitrites and nitrates. In certain subsoils, as pointed out in Chapter 11, fixed ammonium may be present in amounts of up to 40% of the total nitrogen.

The nitrogen content of most forms of humus is about 5.0–5.5%, and the carbon content 50–58%, giving a carbon–nitrogen ratio of near 9 to 12. If the nitrogen were present as protein approximately a third of the humus in soil would consist of nitrogenous complexes. As humus is formed in the soil or compost pile there is a tendency for the final well-decomposed product to have a fairly constant nitrogen content regardless of the composition of the original plant materials from which it was formed. If these were very high in nitrogen, such as green alfalfa, considerable ammonia is released; if deficient in nitrogen, as in wheat straw, the rate of decomposition may be slowed down but all of the nitrogen will be assimilated by the microorganisms and perhaps some additional nitrogen from outside sources, to give a humus of near 5% nitrogen.

The chemical nature of organic nitrogen in soils is a phase of organic matter research that has attracted many workers, partly because of the importance of nitrogen in crop production, and also because it seemed to them that more progress on the chemistry of humus could be made in this area of research, especially by the older methods available. Most of our earlier knowledge was obtained by treating soils with hot acids and then determining the forms of nitrogen released. In his review of these studies Bremner (1965) states that various workers have shown that from 20 to 40% of the total nitrogen in surface soils is in the form of bound amino acids; 5–10% is in the form of combined hexosamines; and about 1% or less is present as purine and pyrimidine derivatives. There is uncertainty as to how these substances are linked up with other portions of the humus complex. Many other organic compounds, such as choline, creatinine and allantoin, have been found in soils in very small amounts. We know that nitrogen is present in chemical combination with lignin degradation products and with other organic molecules. Very little is known with certainty about the chemical nature of the 50% or so of the organic nitrogen that is not released by acid hydrolysis. A fraction of the nitrogen that was once assumed to be organic is now known to be present as fixed ammonium trapped in clay minerals, as discussed in Chapter 11.

The development of chromatographic methods in recent years has greatly aided in the identification and estimation of amino acids in the acid hydrolysates of soil and in other soil organic matter preparations. Bremner (1965) gives a good summary of work of this type. About 20 amino acids are commonly present in acid hydrolysates of soils. In addition, many other compounds, some of which have not been identified, have been found in small amounts by means of paper chromatography. Present information indicates that the amino-acid composition of soils is reasonably constant qualitatively although the quantities of each acid may vary. Trace amounts of free amino acids have also been detected in soils. Certainly large amounts would not be expected to be present since they are such an excellent food for microorganisms.

The nitrogen in soils was at one time believed to be present largely as protein but recent studies have furnished little or no evidence in support of this idea. Kojima (1947) found that 37% of the nitrogen of a muck soil was present as α-amino acids. If calculated as protein, which is unjustified, the total protein present would be in the order of 50–75% of the total organic nitrogen present. Bremner (1949) hydrolyzed six soils and reported that 24–87% of the total soil nitrogen was liberated as α-amino nitrogen; if calculated as protein this would indicate that a minimum of about a third of the soil nitrogen was present in this form. As already stated, proteins have not been isolated from soils and are probably not present in appreciable amounts except in newly-added plant residues and in microbial cells. Presumably much of the amino nitrogen in soils is in the form of amino acids or peptides complexed with quinones or phenolic compounds. Bremner (1965) suggests that some of the bound amino acid nitrogen may be in the form of mucopeptides and teichoic acids, since these polymers are important constituents of bacterial cell walls.

Amino sugars occur in soils as high-molecular weight substances and are believed to be largely of microbial origin. Polysaccharides, antibiotics, mucopeptides and teichoic acids are examples of substances synthesized by microorganisms that contain amino sugars. Bacterial cell walls also contain these sugars. Glucosamine and galactosamine have been found in the acid hydrolysates of humic acid. Hexosamines have also been found in the fulvic acid fraction of soil organic matter and in pyrophosphate extracts of soils. Chitin, which occurs in fungi and in the skeletons of insects, is doubtless present very commonly in soils although there is little direct evidence of this. Stevenson (1957) found 5–11% of the nitrogen in several surface soils to be amino sugar nitrogen. The proportion tended to increase with depth in many soils, the maximum generally occurring in the B-horizon. Native vegetation and drainage had little influence on the distribution of hexosamines.

Purines and pyrimidines that occur in soil in small amounts are probably of bacterial origin, and may be chiefly in DNA. Amides, such as asparagine and glutamine, are known to occur. Many other nitrogenous substances have been found in soils but in insignificant amounts.

Much of the nitrogen not discussed above, amounting to about 50% of the total soil nitrogen, occurs in complexes and mixtures with polysaccharides, lignin degradation products and other substances not yet clearly defined. Some of the nitrogen is present as fixed ammonia and in heterocyclic and aromatic ring compounds.

The tendency for humus formed under a given set of climatic conditions to have a fairly uniform composition regardless of the carbon and nitrogen sources added is well-illustrated by the work of Sowden (1968) and associates (Halstead and Sowden, 1968; Sowden and Atkinson, 1968). They applied comparatively large amounts of common soil amendments yearly to two Canadian soils for 20 years. Table 8.1 shows the nitrogen distribution in these soils at the end of this period. The lack of marked differences in the

TABLE 8.I

NITROGEN DISTRIBUTION IN SAMPLES FROM PLOTS AFTER 20 YEARS OF ADDITION OF AMENDMENTS (from SOWDEN, 1968)

Treatment	*Kjeldahl-N (%)*	*Hexosamine-N**	*Ammonia-N**	*Amino-acid-N**	*N accounted for **	*Acid-soluble N**
Clay soil:						
Control	0.194	3.3	22.4	27.6	53	82
Rye	0.207	4.0	22.0	31.0	57	84
Straw	0.242	4.1	20.8	32.9	58	83
Alfalfa	0.231	4.0	19.6	30.8	54	82
Leaves	0.234	3.4	19.4	30.4	53	80
Peat	0.213	4.0	19.2	32.5	56	83
Muck	0.317	3.9	20.1	32.2	56	82
Manure	0.247	3.3	20.1	32.0	55	82
Sand soil:						
Control	0.085	2.8	19.8	32.4	55	81
Rye	0.098	2.8	21.5	30.7	55	81
Straw	0.116	2.8	21.5	33.1	57	78
Alfalfa	0.107	3.4	20.3	34.3	58	82
Leaves	0.170	2.6	20.4	34.5	57	81
Peat	0.152	2.9	19.3	35.5	58	80
Muck	0.191	2.6	19.6	31.3	54	80
Manure	0.189	2.7	20.6	32.7	56	81

*Expressed as percentage of total soil nitrogen.

nature of the organic nitrogen in the two soils regardless of the composition of the added materials is very striking. As Sowden points out, the muck amendment is, to a degree, an exception but this is to be expected; muck is already a decomposed material and markedly different from the other amendments. These data are in complete harmony with the view that in the process of humus formation the carbon sources undergo extensive biological decomposition followed presumably by chemical combinations to form resistant humus, as Schreiner and Dawson stated many years ago. Considerable work, such as that reported by Wagner and Stevenson (1965), has been done in attempts to determine the number and arrangement of the functional groups involved in humic acid formation.

The work of Stanford et al. (1970) involving the incorporation in soil of five crops of oats, grown with ^{15}N-labelled ammonium sulfate, would indicate that the formation of resistant complexed humus takes place rather rapidly. When the soils were extracted after the five croppings the distribution of the ^{15}N and of the indigenous soil nitrogen among the extracts, and in the acid-soluble and acid-insoluble portions of the soil residues following autoclaving in 0.01 *M* $CaCl_2$, was similar. The authors state that "since appreciable equilibrations between added N^{15} and the more resistant forms of soil organic nitrogen is unlikely, it is postulated that fertilizer nitrogen became incorporated in newly-formed complexes, similar to those already present in the soil."

This comparatively rapid formation of N-containing complexes would seem to offer a logical explanation for greenhouse results obtained by the author and associates (Pinck et al., 1945; 1948a,b), which were unexpected and not adequately explained at the time. In these experiments where large amounts of plant materials were repeatedly incorporated with the soil together with urea or sodium nitrate, only slightly more than half of the fertilizer nitrogen was recovered in the crops. Most of the remainder together with plant carbon remained in the soil as soil organic matter. The nitrogen in this newly-formed organic matter was not readily released even when the soils were kept in fallow for several months; it was doubtless tied up in complexes. The mean release was only about 3% of the added nitrogen, which is in agreement with results reported by Tyler and Broadbent, 1958; Broadbent and Tyler, 1962; Jansson, 1963; Bartholomew, 1965 and Broadbent and Nakashima, 1965, 1967 (see Chapter 6).

Carbohydrates

Carbohydrates constitute the main constituents of plants, with.cellulose the most abundant. In addition, are the various hemicelluloses or polysaccharides, pentosans and polyuronides. Most of these substances, especially cellulose, are readily attacked by many species of soil microorganisms. The result is that the carbohydrate content of humus is very different from that of the plant residues from which most of the humus is derived (Gupta, 1962; Gupta et al, 1963; Gupta and Sowden, 1964). Humus usually contains little cellulose but does contain hemicelluloses and polyuronides. These substances are in part the residues of the original plant materials but most of them are the synthesized gums, slimes and cell walls of the microorganisms that are responsible for decomposition and the formation of humus.

The total carbohydrate content of soils is, according to Mortensen and Himes (1964), in the range of 5–20% of the soil organic matter. Mehta et al. (1961) found that about 10% of the soil organic matter was in the form of polysaccharides. Their extreme heterogeneity with respect to kinds of sugars present indicated strongly that they were predominantly of microbial origin. This is of course as might be expected since the carbohydrates in green plants are decomposed readily in soils and serve as excellent precursors of microbial polysaccharides. Since the bacterial polysaccharides are formed in large part as extracellular gums or capsular materials, which are in turn subject to biological attack, it may seem a little surprising and puzzling that they occur in soils in more than trace amounts. One possible explanation for this is that the soil polysaccharides may be held inside soil aggregates where microorganisms are unable to penetrate so long as the aggregates remain intact (Emerson, 1959; Allison, 1968). The molecular weight of crude polysaccharides has been estimated to be between 10,000 and possibly 400,000. Such large molecules indicate considerable polymerization and complexing, which doubtless helps substantially in protecting them against biological attack.

Polysaccharides are present in fulvic acid, humic acid, and humin fractions of soil organic matter. Extractants remove only a small percentage of the total present and hence determinations must be made by means of hydrolysis followed by analysis of the products. These include hexoses, pentoses and uronic acid. There seems to be no doubt that soil polysaccharides are important constituents of soil organic matter. They have a role in soil structure, aggregation, exchange capacity, may combine with metals, serve as food for microorganisms, and thus are involved in nitrogen availability.

Lignin-like complexes

Lignin is the third most abundant constituent of plant tissues, with cellulose and hemicellulose being first and second, respectively. In the process of decomposition most of the carbon of the two more abundant materials is released as CO_2, whereas lignin decomposes more slowly and less completely. The lignin residues and microbial transformation products become complexed with amino acids and other substances to form very resistant materials.

It was pointed out above that about a third of the organic matter of soils consists of nitrogenous substances (if the nitrogen is calculated as protein) and that 5–20% may be carbohydrate. Fats and waxes may be present to the extent of 2–4%. The remaining 40–60% is made up of complexes, sometimes described as lignin-like. The nature of these is still uncertain and under very active investigation.

There is considerable uncertainty as to the exact structure of lignin, and we also know that lignins from different sources differ chemically. Analytical methods are also far from satisfactory both for the determination of total lignin and for differentiating between lignins from different sources, especially where partial decay has occurred. Unlike cellulose and hemicellulose, lignin is an aromatic compound consisting of a polymer built up from substituted derivatives of phenylpropane (Stevenson, 1964). It is this ring structure that largely accounts for its comparative resistance to microbial attack. According to Stevenson, hydrolysis of plant lignins may yield vanillin, syringaldehyde, coniferaldehyde, *p*-hydroxybenzaldehyde, and others. The basic units of lignin contain many methoxyl and phenolic hydroxyl groups that account for many of its properties.

Gottlieb and Hendricks (1945) applied the alkaline nitrobenzene oxidation technique and high-pressure hydrogenation to soil organic matter in an attempt to determine if such treatments yield the same products as when applied to wood lignin. Various amounts of aldehydic, acidic, and neutral oils were obtained but these oils yielded no definitely characterizable products. Obviously the plant lignin was markedly changed while it was undergoing decomposition in the soil. They suggested that the lignin molecule probably condenses with the production of fused ring structures.

Other changes in the lignin molecule include a decrease in the methoxyl content, an increase in exchange capacity, and a decrease in carbon content. As these changes occur there are reasons to believe that resistance to microbial attack also increases.

The synthesis of lignin-like complexes from sugars by 12 cultures of filamentous fungi was demonstrated by Pinck and Allison (1944). The mycelia of *Cladosporium* and *Helminthosporium* contained 19–24% of these substances that resisted the usual treatment with 72% sulfuric acid. The organisms that produce the largest amounts of lignin-like substances are those that thrive on decaying vegetation at or above the soil surface. The importance of these fungi in humus production in soils is still largely unknown, but the more recent biochemical studies, discussed below, would indicate that they are much more important than formerly believed. Bacteria, so far as known, do not synthesize lignin.

Fats, waxes and resins

The ether- and alcohol-soluble substances, which are usually present to the extent of less than 2% (Fraser, 1955) in the total organic matter of cultivated soils, are commonly considered as impurities by those who are engaged in the study of humus substances (Dubach and Mehta, 1963). They include chiefly oils, fats, waxes, sterols, resinous substances, and glycerides of fatty acids and of long-chain fatty acids. Very little investigational work has been done on these substances and hence our knowledge of them is limited. Some of the high molecular fatty acids are probably present as salts of heavy metals. Complex formation also occurs, otherwise most of these substances would be quickly decomposed by microorganisms. Considerably more than 2% of the total soil organic matter may be in the form of fats, waxes and resins if the organic matter is only partially decomposed, as in peat or forest cover. As humus formation progresses the fatty substances tend to disappear, just as do the carbohydrates.

Organic phosphorus and sulfur compounds

Phosphorus is commonly present in soils in organic form to the extent of 20–50% of the total but this value can be as high as 75%. Usually the percentage increases as the nitrogen content increases and the pH decreases. Carbon, nitrogen and phosphorus are present in the organic matter of mineral soils in the approximate ratio of 110:9:1 by weight. Earlier studies indicated that the organic phosphorus was present largely as nucleic acids, inositol hexaphosphate or phytin, and phospholipids, but later work does not substantiate this view. According to Black (1957) there is little definite evidence for the presence of nucleic acids in soils; inositol phosphates are more abundant than inositol hexaphosphates; and phospholipids are present only in minor amounts. The general conclusion is that we have little quantitative information on the chemical nature of soil organic phosphorus. In a later edition of his book, Black (1968) states that at present our knowledge of the identified organic phosphorus compounds shows 2% present in nucleic acids, 1% in phospholipids, and 35% in inositol phosphates; the nature of the remainder is unknown.

Sulfur is present in soils in organic form to widely varying degrees but in the better soils 50% of the total is likely to be organic. Organic nitrogen and organic sulfur tend to vary similarly, the nitrogen–sulfur ratio commonly varying over the range of 8–12. Sulfur is a constituent of the amino acids cystine and cysteine, which are found in many proteins. Reagents that extract organic matter from soil also extract considerable sulfur, indicating that much of it is organic in nature (Freney, 1961; Freney and Stevenson, 1966). It is found in the fulvic acid fraction. The chemical nature of organic sulfur in soils is largely unknown.

Metal–organic complexes

Soil organic matter complexes by chelation or otherwise with metals in soils, including K, Ca, Mg, Al, Cu, Zn, Fe, Mn and various other trace elements (Bremner et al., 1946; Broadbent, 1957; Broadbent and Ott, 1957; Lewis and Broadbent, 1961a,b; Khanna and Stevenson, 1962; Schnitzer and Skinner, 1963a,b, 1964, 1965; Wright and Schnitzer, 1963; Randhawa and Broadbent, 1965a,b; Schnitzer, 1968). Broadbent and Ott (1957) found that organic matter preparations formed complexes with cations rapidly, even in very dilute solution. The amount formed depended on the nature and concentration of the cation, time of contact, and pH. The formation of metal complexes may render the organic matter water-insoluble (Bremner et al., 1946) and less readily attacked by microorganisms. The metal is also made highly immobile, which should markedly affect its degree of leaching. Very little exact information is available on the organic constituents involved or the nature of the binding sites. The active sites are probably phenols, carboxyls and possibly imide nitrogen.

Biochemistry of humus formation

Humus formation, as has been emphasized above, is largely a biochemical process. Much of the research has, however, been of a chemical nature involving many methods of determination of the chemical nature of the final product, and with comparatively little attention being given to the direct contribution of microorganisms to the formation of humic acids. The partial failure of organic chemical methods to solve the problem, along with the introduction of tracer techniques and the development of new chemical and physical techniques, has resulted in a marked change in methods of research during the past ten years. At an accelerated rate, the emphasis is now being placed on the role of microorganisms in humus synthesis. Just as Schreiner and Dawson said years ago, it is now realized that it is more profitable to follow the steps in the synthesis of humic acids than to try to tear up the final product, and then attempt to figure out how the big molecules were formed.

At the present time there seems to be general agreement that microorganisms play major direct and indirect roles in humic acid formation. Marked biochemical advances are being made, and there is already fairly close agreement among workers as to how humus is formed, and its overall chemical nature. Each worker emphasizes a different phase of the process based on his own research and observations. Below are reviewed contributions from several representative laboratories that when considered as a whole seem to summarize the present state of knowledge of the subject as seen by leading organic chemists and biochemists.

Whitehead and Tinsley (1963) state that "humus represents a quasi-equilibrium stage in the decomposition of plant and microbial constituents, and as such its chemical composition is likely to fluctuate to some extent with variations in these materials. The major components, apart from polysaccharides, are thought to be polymers formed from the recombination of units such as quinones, amino-acids and aldehydes, compounds of varied complexity synthesized from simple molecules by soil microorganisms, particularly fungi, and possibly cell wall material from the microorganisms. Since most of these components have reactive side groups such as —COOH, —NH_2 and —OH, there are likely to be linkages between them giving finally a complex three-dimensional structure. Soil organic matter also retains polyvalent metal ions by chelation, and forms linkages to the clay colloids. The consequent difficulty of extracting it from the soil presents a major problem in the elucidation of its composition, for methods which extract a high proportion of the soil organic matter generally cause considerable chemical modification during the process, and methods which avoid modification extract only a small proportion which may not be representative of the total."

Whitehead and Tinsley state further that "some fractionation of humic acid has been achieved by chromatographic and electrophoretic procedures, but it has not been possible to detect any clear-cut differences between the fractions. The predominantly aromatic or heterocyclic nature of humus, apart from the polysaccharide fraction, is now well established, but the inability to identify distinct components has lead to the view that humus results from the copolymerization of a number of different small units. Evidence of the units involved is sparse, since very few small molecular aromatic compounds have actually been detected in soils." When humus has been degraded by oxidative procedures, a wide variety of phenols, phenolic aldehydes and phenolic acids have been obtained but the identified products account for only 0.5–1.3% of the original humic acid.

The work of Swaby and Ladd (1962) dealing with the nature and origin of humic acids in soils is especially noteworthy because of some new ideas that they proposed. In their work with soil humic acid preparations they detected small amounts of phenolic substances and numerous carboxyl groups but no proteins. Over 20 amino acids, some ammonia and traces of indoles were detected after acid hydrolysis. They concluded, as have many other workers, that lignin constitutes a negligible proportion of humic acid even in peats.

Artificial humic acids were produced, either chemically or enzymatically, from a variety of phenols, from sulphonated napthoquinone, and from *p*-benzoquinone, together with numerous amino acids. Microbial decomposition of both natural and artificial humic acids was usually negligible. When model humic acids were prepared by reacting quinones formed from phenols, usually with amino acids present, it was observed that oxidation, polymerization, and polycondensation were more rapid in the presence of amino acids than in their absence. Evidently the amino acids participate in these reactions. Colorless products were formed initially which gradually darkened to reddish-brown and then brownish-black. These humic acids had many physical and chemical properties that corresponded closely to those of natural humic acids.

As a result of these studies Swaby and Ladd concluded that "it seems more likely that humic acids consist of amino acids, rather than proteins, combined with phenols or quinones, rather than with lignin. It is suggested that the amino acids are condensed through the amino groups to quinones, leaving the carboxyl groups free for titration. If the diamino-amino acid, lysine, and the thiol-containing cysteine occurred, then they would probably cross-link with neighbouring quinones. Such a three-dimensional co-polymer consisting of many different amino acid, phenol, and quinone units without ordered sequence would be amorphous, and having isolated resonance groups, would absorb light of all wavelengths and appear black. It would be precipitated by heavy metals, and by acids, be soluble in alkalis owing to its free carboxyl groups, and be slightly soluble in organic solvents owing to its predominantly condensed aromatic nature."

Swaby and Ladd further observed that soil humic acid was difficult to decompose even though lignin and clays were absent and only traces of silica, iron and aluminum were present. Soils that had been buried beneath volcanic ash for 3,000 years contained amino acids and phenols that differed little from those from recently formed humates. These observations suggest that resistance was due to the molecular structure. The authors point out that as the size of polymers increases the ease of degradation by enzymes decreases, and that linear co-polymers with regular repeating units are decomposed more readily than those with dislocation. Also, molecules that are weakly cross-linked by van der Waals or hydrogen bonds are more readily attacked than those strongly held by covalent bonds. They make the logical suggestion that "the resistance of humic acid to microbial and to chemical decomposition could be explained if it were a large spherical molecule, consisting of many heterogeneous units, irregularly crosslinked by different covalent bonds, so that innumerable extra-cellular enzymes from many different microorganisms would be needed to dismember it piece by piece from the outer surface. This would be a lengthy process unless a greater variety of microorganisms were encouraged by the addition of readily decomposable debris."

The above concept of the possible chemical nature of humic acids poses questions as to how and where they are formed, considering that the building units (amino acids, phenols, quinones and aldehydes), are readily attacked by microorganisms. They could not be expected to accumulate in soils except possibly in the micropores that are too small for penetration by bacteria. Swaby and Ladd hypothesize, therefore, that humus molecules are rapidly polycondensed or polymerized from free radicals formed by enzymatic action in high concentrations of monomeric substances where microorganisms capable of attacking them are absent. They state that suitable conditions for this are found in plant and microbial cells immediately after death when autolytic enzymes are active but cell destruction has not yet begun. During this period amino acids may be formed from proteins by hydrolysis, and quinones and polyphenols by oxidation. They believed that the humic molecules may form rapidly inside these cells, chiefly by chemical polymerization, while the concentration of reactants is high. When released into the soil through cell decomposition the newly-formed humates may be adsorbed by clays and thus be further protected from biological attack.

This theory of Swaby and Ladd assumes that native lignin may be the source of phenols and quinones that combine with amino acids or ammonia to form polymers but, until decomposed, lignin is not active in humic acid formation. Since humic acid shows poor crystallinity it is probably not synthesized enzymatically but by heterogeneous chemical catalysis. They conclude that "it is certainly not a mere mixture of scraps of cellular substances which have defied microbial decomposition, but is more like a resin formed by chaotic chemical combination of monomers produced enzymatically."

Although this hypothesis dealing with the origin and nature of humic acid remains to be proven, it is certainly intriguing and seems to account for many of the known facts that have in the past been very perplexing. Some workers may question the implication that humic acid is formed largely or wholly in plant and microbial cells but the newer evidence, cited below, is in harmony with this idea; in fact, humic acid formation may not even be dependent upon the presence of lignin degradation products. We know that it can form in the absence of higher plants, as in compost piles, but it is in such environments that microorganisms are very abundant. Perhaps it is in these micro cells that most of the humic acid is synthesized.

A good discussion of our knowledge of lignin and humic acids is given by Hurst and Burges (1967). Evidence suggests that both lignin and flavonoid residues contribute to humic acid but information on the nature of the humification process is limited. The crux of the problem, they stated, is "the process by which a highly heterogeneous assemblage of phenols is converted to a series of high-molecular-weight compounds with an overall similarity in properties." One view is that the true nature of humic acid lies in a hard-core unit which has yet to be characterized. In their discussion of this possibility they say that "there is no a priori reason to believe that a core unit would be produced de novo by the sudden association in the soil of phenolic nuclei followed by oxidation and free-radical polymerization. A more satisfying explanation is that the molecule grows by the stepwise addition of free phenols liberated by microbial metabolism and that these are then crosslinked, perhaps by biphenyl carbon–carbon links or phenol–ether bridges, a process referred to as humification or condensation. In this case we may expect to find monomers in all states of attachment, some loosely and more readily removed by nitrobenzene oxidation or sodium amalgam reduction and others approaching the more tightly condensed condition of the core unit. There would be no sharp discontinuity between the core and more recently attached phenolic residues. Any distinction between the two would be an arbitrary one, and the term 'humic acid' could be applied with equal validity to either the whole complex or an ill-defined core unit."

Tiurin and Kononova (1962) emphasize the importance of microorganisms (and animals) in all links of the humus formation process – in the decomposition of initial organic substances and in their profound change, followed by formation of structural units and their further condensation. Their view is that the participation of microorganisms is not limited just to decomposition. They observed that when *Penicillium, Aspergillus*, and *Actinomycetes* were grown on a medium containing sugar as the only source of organic matter, dark, humus-like substances were formed together with amino acids, peptides and polyphenols that serve as structural units for humic substances. When plant materials are the energy source a number of compounds, especially polyphenols and amino acids, are formed that serve as precursors of humic substances. The polyphenols are oxidized to quinones, which react with other components, in particular with amino acids or peptides. They state that "the main path of oxidation of polyphenols to quinones in soil is biochemical and is brought about with the participation of enzymes of the phenol-oxidase type produced by numerous groups of microorganisms (especially by fungi and actinomycetes)." Humic substances formed in culture media or from plant residues are considered by these workers as only primary forms of humic acids. The more mature type of humus is formed from these primary forms as a result of the "activity of microorganisms, hydrothermal conditions, and chemical and physiochemical soil properties." They also stress the importance of fauna in the humification of organic residues; for example, they consider that the condensation of substances is promoted by the oxidase-enzymes produced in the intestines of animals.

Flaig (1966) has presented data that agree closely with many of the ideas of Swaby and Ladd (1962) and Whitehead and Tinsley (1963). He states that during humification of plant residues, compounds occur which, from their chemical composition, appear to be lignin decomposition products. During oxidative decomposition of these compounds quinones and other products are formed, and the methoxyl content of the lignin fractions decreases. By demethylation, polyphenols are also formed. From these studies, using the ^{14}C-labelling technique, he concludes that degradation of lignin decomposition products begins in the side chain, and a further degradation occurs by cleavage of the ring, especially after 1,2-diphenols are formed by demethylation. He states further that "in the presence of phenol-oxidases a dehydrogenating polymerization occurs by which the monomers are connected not only by the side chain but also by the aromatic ring. With increased degradation of the side chain with three carbon atoms an increased connection of the rings occurs." He considers that nitrogen is an integral part of the humic acid molecule. A part of this can be hydrolyzed as amino acids but presumably the remainder is heterocyclic bound.

Flaig has presented an excellent summary of our present knowledge of how parent materials may be converted into the dark-colored organic substances in the soil which are designated as humic substances. There is not sufficient space here to discuss this involved subject in detail, but the main facts are given above and in condensed form in Fig.8.1, drawn by Flaig (1966). The chemical substances and reactions involved are discussed rather fully by him.

The phenols that participate in the formation of humic acids can, according to Flaig and Haider (1968), originate from the lignin of plants, or they may be synthesized by microorganisms. By the use of tracer techniques they showed that in the microbial degradation of "synthetic" lignins the cleavage of the ring is an important reaction. They state that "from humic acids, which are synthesized through the metabolism of some microorganisms, resorcinol derivatives could be identified after reductive cleavage. In the case of *Epicoccum nigrum* the biosynthesis of orsellinic and cresorsellinic acid from aliphatic precursors was observed; these two acids were transformed by the fungus into about 20 phenols. The formation of humic acids in the culture media and the mycelium of this organism occurs only then, if auto-oxidizable hydroxyhydroquinone or pyrogallol derivatives are formed. The smaller lignin degradation products are polymerized into the

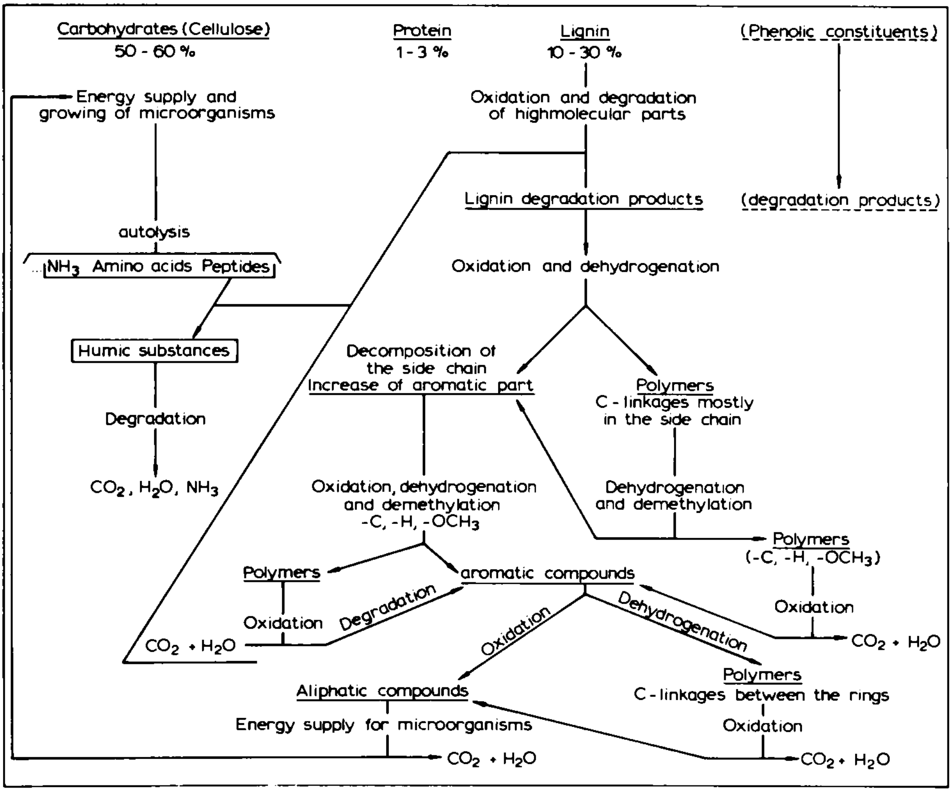

Fig.8.1. Processes of transformation of organic substances in soil. (From Flaig, 1966.)

fungal humic acids. This occurs by a transformation and introduction of hydroxyl groups. In this case the benzene nucleus is scarcely degraded." Further studies dealing with the role of this organism in humic acid synthesis are reported by Haider and Martin (1967) and Martin et al. (1967).

Chemical studies with the alkali-soluble material obtained from the spores of *Aspergillus niger* by Kang and Felbeck (1965) showed the spore extract to have properties similar to those of soil humic acids. From these results they hypothesize that humic acid in soil could be entirely of microbial origin, although this is not yet proven. Various soil microorganisms would be expected to produce a variety of materials similar to those found in soil humus, which is known to be made up of heterogeneous polymers. They suggest that "considerable insight into the structure of humic acid and simplification of the problem might be provided in the future by a concerted examination of the humus-like products obtained from a single microbial species." The evidence seems to be accumulating that humus is much more of a synthetic microbial product than a strictly chemically-derived material; very likely it is a product of both processes.

Stability of humus

The resistance of soil organic matter to biological decomposition under natural conditions has long been known but probably somewhat underestimated until the advent of ^{14}C dating. Results obtained recently by this technique show quantitatively the age of soil carbon, and by selection of samples and their fractionation the technique can be used to throw light on the reasons for the stability.

Radiocarbon age determinations

Brown (1965) published a list of determinations made of the age of frozen peats, soils and other organic materials from the region of Barrow, Alaska. Samples taken from depths of less than one meter had ages ranging from 1,775 ± 120 to 11,050 ± 350 years. One sample from a depth of 2.1 m had an age of 25,300 ± 2,300 years. The organic matter in a sample of Arctic Brown soil, taken at the surface, had an age of 3,000 ± 130 years, but the humic acid portion of this sample had a shorter age, namely 2,100 ± 180 years. Although these data are extremely interesting, they furnish little information on why soil organic matter in soils of the Temperate Zone is so stable. There is negligible biological activity in soils that are frozen most or all of the time.

Surface soils taken from Iowa and North Dakota were reported by Broecker et al. (1956) and by Smith et al. (1960) as having radiocarbon ages of 210 ± 130 to 440 ± 120 years. Corrections for the Suess effect, made subsequent to the original publication, adds approximately 200 years to these values, making the range about 410–640 years. One of these soils, the Edina from Iowa, which had a corrected age of about 610 years for the surface soil had an age of 1,040 years for the A_2-horizon. A humus podzol from Georgia, high in sesquioxides, had an age of 1,350 years; a similar type soil from Holland had a radiocarbon age of 1,140 years. Neugebauer and Żakosek (1962) reported that humus from the A_2-horizon of a montmorillonitic soil had a ^{14}C age of 2,770 ± 140 years.

Radiocarbon data (unpublished) for a Cheyenne fine sandy loam, 0–6 inch depth, from Mandan, North Dakota, were supplied through the courtesy of L.T. Alexander, formerly of the Soil Conservation Service, U.S. Department of Agriculture, Beltsville, Maryland. The age of the virgin Cheyenne grassland soil was 1,175 ± 100 years; a manured plum orchard 880 ± 75 years; and a clean cultivated area 1,900 ± 120 years. As would be expected, these data show very clearly that where additions of fresh organic matter are made regularly the average age of the soil carbon is considerably less than where none is added. As continued biological oxidation removes much of the younger non-humic fraction of the organic matter, the average age of the residual stable humic fraction increases. Obviously, the humic fraction of soil organic matter is far more resistant to microbial attack than was generally believed before carbon dating was introduced.

Analyses of the surface layer of a Bridgeport loam from Sheridan, Wyoming, were also supplied by L.T. Alexander. The carbon age of the surface sod-soil layer, and also of a sample of soil from the corn–fallow–corn plot was 3,280 years; that of the clay fraction from the virgin soil was 6,690 years; and of the soil from the continuous wheat plot

1,895 years. These data emphasize even more strongly that the humic portion of soil organic matter is so highly resistant to biological attack that it is essentially inert. Evidently the clay protects the humic fraction but it is doubtful if this is the major factor involved. Since present evidence indicates that only a small fraction of humic substances enter into the lamellar spaces of 2:1 layer clays, it would seem likely that chemical composition is the major factor responsible for the extreme resistance of old organic matter in soils.

Campbell (1965) made an extensive study of the carbon-dating method as applied to the study of problems in soil organic matter investigations and found it to be very satisfactory. The mean residence times of humus from the A_p-horizon of 5 Saskatchewan soils ranged from 250 years for a gray-wooded podzolic soil to 1000 years for black chernozemic soils; the humus from chernozems from Alberta was even older. The calcium humates and non-hydrolyzable humic acids of the chernozems had an age of 1,400 years, whereas the age of the humic acid hydrolysate was only 25 years. This hydrolysate, which was a small fraction of the total humus, accounted for 80% of the nitrogen released per annum; the major portion of the soil humus was found to be inert. In general, the humus of podzolic soils was much more labile than that of chernozems.

Suggested explanations

The stability, or resistance of soil organic matter to biological and chemical attack, constitutes one of its most important and puzzling characteristics. In the numerous chemical studies that have been conducted it is common for only 20–50% of the organic C and N substances to be released as comparatively simple compounds that can be identified. The percentage of the C and N that is apparently bound up in complexes is dependent to some extent on the organic matter itself (proportion of humic and non-humic materials), and even more on the methods used to fractionate the organic matter, and to separate it from colloidal clay.

The chief ideas that have been advanced to explain the resistance of humic matter to chemical and biological attack are the following; (1) lignin may react with protein; (2) oxidized lignins may react with ammonia: (3) carbohydrates or their derivatives may react with amino compounds; (4) nitrite reacts with organic matter; (5) non-hydrolyzable nitrogen may be in the form of heterotrophic nitrogen compounds; (6) the organic compounds are trapped in clay lattices; (7) organic substances react with various mineral elements to form metal-organic matter complexes; (8) tannins form complexes with proteins (Basaraba and Starkey, 1966; Benoit and Starkey, 1968; Lewis and Starkey, 1968); and (9) phenolic substances or quinones react with amino acids. Bremner (1965) discusses most of these theories and concludes that "a combination of these theories provides a reasonably satisfactory explanation of the stability of the organic nitrogen complexes in soils." Since there is little or no evidence that either protein or lignin remains in soils unchanged for any great length of time, it seems to me that this conclusion of Bremner's is a little too broad. Certainly more than one mechanism is involved but recent evidence seems to weigh heavily toward the ideas presented early by Schreiner and Dawson (1927) and more recently by Swaby and Ladd (1962), Whitehead and Tinsley (1963) and Flaig (1966). Not all of their views are necessarily correct but it does seem that the resistance of the organic matter complex is due chiefly to its chemical (and physical) composition. Large, spherical, phenolic-amino acid cross-linked polymers, possibly with inorganic elements or oxides bound in the complex, might well be expected to be extremely resistant to biological attack under soil conditions (also see Chapter 6).

Another factor of secondary importance that needs to be considered in attempts to account for the permanence of organic matter in soils is the matter of accessibility of microorganisms to the substrate, regardless of whether it is or is not adsorbed. Soil bacteria are commonly about a half micron in diameter and hence cannot penetrate soil pores that are smaller than this. Fungi and actinomycetes are even larger than bacteria, and the animal population is largely in the range of visibility to the naked eye. Enzymes produced by the living population may be able to penetrate into the small pores but they, like other proteins, may be adsorbed before they penetrate into the centers of aggregates. Since even uncultivated soils constantly undergo some movement as a result of physical forces and the activities of the animal and plant population, it is improbable that the inability of bacteria to penetrate soil micropores would account for much of the stability of soil organic matter over periods of a century or more. During periods of only a few years it might be a factor of considerable importance.

Hypotheses on structure of humus

Felbeck Jr. (1965a) summarizes at some length the hypotheses that have been suggested on the structure of humic substances. Attention is given to the ideas of Thiele and Kettner (1953), Flaig (1959, 1960, 1964), Kononova (1961), Swaby and Ladd (1962) and Felbeck Jr. (1965a,b). These hypotheses cannot be discussed here in detail. Felbeck's general summary of the various ideas follows.

"Most of the hypotheses appear to have several aspects in common: humic substances are amorphous, three-dimensional polymeric, acidic substances of high molecular weight with a more or less aromatic nature. Most hypotheses also agree that at least the humic acid and humin fractions are chemically homogeneous but heterogeneous as to molecular weight. It is also generally believed that no one specific structural formula will adequately represent humic substances. Rather, most hypotheses suggest a 'type' or 'skeletal' structure in which only the general aspects are included, the details (e.g., specific location and number of functional groups) being omitted. The hypotheses differ primarily in the nature of the structural nucleus, i.e., whether it is primarily benzenoid, phenolic, quinonic, or heterocyclic in nature, whether the N is a fundamental part of such nucleus or is an accidental contaminant, and whether there is a reasonable degree of uniformity in the nucleus or whether there is lack of uniformity as reflected in a number of structural units randomly distributed throughout the nucleus."

REFERENCES

Allison, F.E., 1968. *Science*, 106: 136–143.

Bartholomew, W.V., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 285–306.

Basaraba, J. and Starkey, R.L., 1966. *Soil Sci.*, 101: 17–23.

Benoit, R.E. and Starkey, R.L., 1968. *Soil Sci.*, 105: 203–208.

Black, C.A., 1957. *Soil-plant Relationships.* Wiley, New York, N.Y., 332 pp.

Black, C.A., 1968. *Soil-plant Relationships.* Wiley, New York, N.Y., 792 pp.

Bremner, J.M., Mann, P.J.G., Heintze S.G. and Lees, H., 1946. *Nature*, 158: 790–791.

Bremner, J.M., 1949. *J. Agric. Sci.*, 39(2): 183–193.

Bremner, J.M., 1951. *J. Soil Sci.*, 2: 67–82.

Bremner, J.M., 1954. *J. Soil Sci.*, 5: 214–232.

Bremner, J.M., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 93–149.

Broadbent, F.E., 1953. *Adv. Agron.*, 5: 153–183.

Broadbent, F.E., 1955. *Soil Sci.*, 79: 107–114.

Broadbent, F.E., 1957. In: *Soil – Yearbook of Agriculture, 1957.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., pp. 151–157.

Broadbent, F.E. and Nakashima, T., 1965. *Proc. Soil Sci. Soc. Am.*, 29: 55–60.

Broadbent, F.E. and Nakashima, T., 1967. *Proc. Soil Sci. Soc. Am.*, 31: 648–652.

Broadbent, F.E. and Ott, J.B., 1957. *Soil Sci.*, 83: 419–427.

Broadbent, F.E. and Tyler, K.B., 1962. *Proc. Soil Sci. Soc. Am.*, 26: 459–462.

Broecker, W.S., Kulp, J.L. and Tucek, C.S., 1956. *Science*, 124: 154–165.

Brown, J. 1965. Arctic. *J. Arct. Inst. N. Am.*, 18: 36–48.

Campbell, C.A., 1965. Dissertation, Dept. Soil Sci., Univ. Sask., Saskatoon, Sask.

Dawson, J.E., 1950. In: *Agricultural Chemistry.* Van Nostrand, New York, N.Y., 1: 778–797.

Dawson, J.E., 1956. *Adv. Agron.*, 8: 377–401.

Dubach, P. and Mehta, N.C. 1963. *Soils Fert.*, 26: 293–300.

Emerson, W.W., 1959. *J. Soil Sci.*, 10: 235–244.

Felbeck Jr., G.T., 1965a. *Adv. Agron.*, 17: 327–368.

Felbeck Jr., G.T., 1965b. *Proc. Soil Sci. Soc. Am.*, 29: 48–55.

Flaig, W., 1959. *Proc. Int. Congr. Biochem., 4th, Vienna, 1958*, 2: 227–246.

Flaig, W., 1960. *Sci. Proc. R. Dublin Soc., Ser. A*, 1: 149–162.

Flaig, W., 1964. *Geochim. Cosmochim. Acta*, 28: 1523–1535.

Flaig, W., 1966. In: *The Use of Isotopes in Soil Organic Matter Studies.* Pergamon, New York, N.Y., pp. 103–127.

Flaig, W. and Haider, K., 1968. *Trans. Int. Congr. Soil Sci. 9th, Adelaide, S.A.*, 3: 175–182.

Fraser, G.K., 1955. In: F.E. Bear (Editor), *Chemistry of the Soil. Am. Chem. Soc. Monogr., Ser.* Reinhold, New York, N.Y., 126: 149–176.

Freney, J.R., 1961. *Aust. J. Agric. Res.*, 12: 429–432.

Freney, J.R. and Stevenson, F.J., 1966. *Soil Sci.*, 101: 307–316.

Gottlieb, S. and Hendricks, S.B., 1945. *Proc. Soil Sci. Soc. Am.*, 10: 117–125.

Gupta, U.C., 1962. *Soils Fert.*, 25: 255–257.

Gupta, U.C., Sowden, F.J. and Stobbe, P.C., 1963. *Proc. Soil Sci. Soc. Am.*, 27: 380–382.

Gupta, U.C. and Sowden, F.J., 1964. *Soil Sci.*, 97: 328–333.

Haider, K. and Martin, J.P., 1967. *Proc. Soil Sci. Soc. Am.*, 31: 766–772.

Halstead, R.J. and Sowden, F.J., 1968. *Can. J. Soil Sci.*, 48: 341–348.

Hurst, H.M. and Burges, N.A., 1967. In: A.D. McLaren and G.H. Peterson (Editors), *Soil Biochemistry.* Marcel and Dekker, New York, N.Y., pp. 260–286.

Jansson, S.L., 1963. *Soil Sci.*, 95: 31–37.

Kang, K.S. and Felbeck Jr., G.T., 1965. *Soil Sci.*, 99: 175–181.

Khanna, S.S. and Stevenson, F.J., 1962. *Soil Sci.*, 93: 298–305.

Kojima, R.T., 1947. *Soil Sci.*, 64: 157–165.

Kononova, M.M., 1961. *Soil Organic Matter – Its Nature, Its Role in Soil Formation and in Soil*

Fertility (translated by T.Z. Nowakowski and G.A. Greenwood). Pergamon, New York, N.Y., 450 pp.

Lewis, J.A. and Starkey, R.L., 1968. *Soil Sci.*, 106: 241–247.

Lewis, T.E. and Broadbent, F.E., 1961a. *Soil Sci.*, 91: 341–348.

Lewis, T.E. and Broadbent, F.E., 1961b. *Soil Sci.*, 91: 393–399.

Martin, J.P., Richards, S.J. and Haider, K., 1967. *Proc. Soil Sci. Soc. Am.*, 31: 657–662.

Mehta, N.C., Dubach, P. and Von Deuel, H., 1961. *Adv. Carbohydr. Chem.*, 16: 335–355.

Mortensen, J.L., 1963. *Proc. Soil Sci. Soc. Am.*, 27: 179–186.

Mortensen, J.L. and Himes, F.L., 1964. In: F.E. Bear (Editor), *Chemistry of the Soil.* Reinhold, New York, N.Y., 2nd ed., pp. 206–241.

Neugebauer, V. and Zakosek, H., 1962. *Notizbl. Hess. Landesamtes Bodenforsch.*, 90: 341–353. (Abstr. in: *Soils Fert.*, 26: 249.)

Pinck, L.A. and Allison, F.E., 1944. *Soil Sci.*, 57: 155–161.

Pinck, L.A., Allison, F.E. and Gaddy, V.L., 1945. *Proc. Soil Sci. Am.*, 10: 230–234.

Pinck, L.A., Allison, F.E. and Gaddy, V.L., 1948a. *Soil Sci.*, 66: 39–52.

Pinck, L.A., Allison, F.E. and Gaddy, V.L., 1948b. *J. Am. Soc. Agron.*, 40: 237–248.

Randhawa, N.S. and Broadbent, F.E., 1965a. *Soil Sci.*, 99: 295–300.

Randhawa, N.S. and Broadbent, F.E., 1965b. *Soil Sci.*, 99: 362–366.

Russell, E.W., 1961. *Soil Conditions and Plant Growth.* Longmans Green, London, 9th ed., XVI, 688 pp.

Scheffer, F. and Ulrich, B., 1960. *Humus and Humusdüngung.* Ferdinand Enke, Stuttgart, 266 pp.

Schnitzer, M., 1968. *Trans. Int. Congr. Soil Sci., 9th, Adelaide, S.A.*, 1: 635–644.

Schnitzer, M. and Skinner, S.I.M., 1963a. *Soil Sci.*, 96: 86–93.

Schnitzer, M. and Skinner, S. I. M., 1963b. *Soil Sci.*, 96: 181–186.

Schnitzer, M. and Skinner, S. I. M., 1964. *Soil Sci.*, 98: 197–203.

Schnitzer, M. and Skinner, S. I. M., 1965. *Soil Sci.*, 99: 278–284

Schreiner, O. and Dawson, P.R., 1927. *Trans. Int. Congr. Soil Sci., 1st, Comm.*, 3: 255–263.

Smith, G.D. et al., 1960. In: *Soil Classification – a Comprehensive System, 7th Approximation.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington D.C., 265 pp.

Sowden, F.J., 1968. *Can. J. Soil Sci.*, 48: 331–339.

Sowden, F.J. and Atkinson, H.J. 1968. *Can. J. Soil Sci.*, 48: 323–330.

Stanford, G., Legg, J.O. and Chichester, F.W., 1970. *Plant and Soil*, 33: 425–435.

Stevenson, F.J., 1957. *Soil Sci.*, 84: 99–106.

Stevenson, F.J., 1964. In: V. Sauchelli (Editor), *Fertilizer Nitrogen – Its Chemistry and Technology. Am. Chem. Soc. Monogr.*, 161: 18–39.

Swaby, R.J. and Ladd, J.N., 1962. *Trans. J. Meet. Comm. IV, V, Int. Soil Sci. Soc., N.Z.*, pp. 197–202.

Thiele, H. and Kettner, H., 1953. *Kolloid-Z.*, 130: 131 (translated by R.G. White).

Tiurin, I.V. and Kononova, M.M., 1962. *Trans. J. Meet. Comm. IV, V. Int. Soc. Soil Sci., N.Z.*, pp.203–219.

Tyler, K.B. and Broadbent, F.E., 1958. *Proc. Soil. Sci. Soc. Am.*, 22: 231–234.

Van Dijk, H., 1966. In: *The Use of Isotopes in Soil Organic Matter Studies.* Pergamon, New York, N.Y., pp. 129–141.

Wagner, G.H. and Stevenson, F.J., 1965. *Proc. Soil Sci. Soc. Am.*, 29: 43–48.

Waksman, S.A., 1932. *Principles of Soil Microbiology.* Williams and Wilkins, Baltimore, Md., 2nd ed., 894 pp.

Waksman, S.A., 1936. *Ann. Rev. Biochem.*, 5: 561–584.

Waksman, S.A., 1938. *Humus.* Williams and Wilkins, Baltimore, Md., 2nd ed., 526 pp.

Waksman, S.A. and Stevens, K.R., 1928a. *Soil Sci.*, 26: 113–137.

Waksman, S.A. and Stevens, K.R., 1928b. *Soil Sci.*, 26: 239–252.

Waksman, S.A. and Stevens, K.R., 1929a. *Soil Sci.*, 27: 271–281.

Waksman, S.A. and Stevens, K.R., 1929b. *Soil Sci.*, 27: 389–398.

Waksman, S.A. and Stevens, K.R., 1930a. *Ind. Eng. Chem., Anal. Ed.*, 2: 167.

Waksman, S.A. and Stevens, K.R., 1930b. *Soil Sci.*, 30: 97–116.

Whitehead, D.C. and Tinsley, J., 1963. *J. Sci. Food Agric.*, 14: 849–857.

Wright, J.R. and Schnitzer, M., 1963. *Proc. Soil Sci. Soc. Am.*, 27: 171–176.

Chapter 9

THE INTERACTION OF ORGANIC MATTER WITH CLAYS

INTRODUCTION

Many types of organic substances can react with mineral substances in soils to form organic–inorganic complexes of various degrees of stability against biological and chemical attack. Our knowledge of the detailed mechanisms of interaction, and exact reasons for the stability of many of these complexes, is still extremely limited. In fact, there is scarcely a phase of soil science, with the possible exception of the chemical constitution of humus, that is less understood than the physics and chemistry involved in the reactions of organic matter with clays. This is not surprising when one considers the many possibilities and factors involved in the reactions. The surfaces of each of the reactants may differ widely, and the magnitude and distribution of the charges are not well understood. Ordinarily, complex formation in soils does not involve the combination of a pure organic compound with a clay mineral of known composition and structure. More often the clay may be coated with one or more layers of the oxides or hydroxides of iron, aluminum or silicon. Many other inorganic substances may also be present in lesser amounts. Under natural conditions the organic material consists of many types of compounds, but of most practical importance are the more thoroughly decomposed materials that constitute humus. The complexities are great and research in the field has been comparatively limited.

As an introduction to this discussion it is well to give the summary from Russell (1961). He states that "a soil may hold humus by five different mechanisms; simple isolated masses of humus, insoluble metal complexes, humus held on positively charged spots in the soil, humus in or on clay interlayers and humus in or on silicates soluble in cold dilute hydrofluoric acid. The first humus group can sometimes be separated from the main mass of the soil by a flotation technique. The second group, which may sometimes include the first, can only be dispersed when the metals have been replaced by, say, sodium ions, which can be done by treating the soil with a salt whose anions form stable soluble complexes with the metallic ions responsible, and which one would expect to be done equally well by the use of suitable cation-exchange resins. The third group is displaced by sodium hydroxide, for the alkalinity of this solution decreases the positive charges on the mineral colloids; but since it increases the negative charges on the humus, it will also disperse humus held by other mechanisms. Little can be said about the fourth and fifth mechanisms – this is, the humus released by hydrofluoric acid – but it may include an important part of the clay–humus complex."

MECHANISMS OF INTERACTION

Organic substances are held to the surface of clays by both Coulomb forces between ions and also by van der Waals attraction of molecules to the surface (Hendricks, 1941; Grim et al., 1947; Talibudeen, 1950). Table 9.I, taken from Greenland (1965), lists the bonding forces that may be involved, and gives examples. It will be noted that the forces that are active in clay–organic complex formation are the same as those acting in other situations where atoms and molecules are in close proximity.

TABLE 9.I

FORCES INVOLVED IN THE INTERACTION BETWEEN CLAYS AND ORGANIC COMPOUNDS (from GREENLAND, 1965)

(*1*) *Coulombic attractions between*	negatively charged surface and positively charged organic compound		
	positively charged surface, or ion or oligo-ion* at surface, and organic anion		
(*2*) *van der Waals forces, composed of:*			
(*a*) *Polar:*	charge-dipole interactions	between	surface and organic compound adsorbed molecules of similar species adsorbed molecules of dissimilar species
	dipole-dipole interactions (including H-bonding)		
	charge-induced dipole interactions		
	dipole-induced dipole interactions		
(*b*) *Non-polar:*	dispersion forces		

*e.g., positively charged hydroxy aluminum oligomers.

When comparatively small known organic molecules are involved, the types and magnitude of the main forces can usually be estimated with a fair degree of accuracy. However, in soils where substances of widely varying sizes are subject to adsorption and where the exact nature of the reacting substances is largely unknown, an accurate analysis or estimation of the magnitude of the various forces involved is all but impossible. The study is especially complex where a large organic molecule reacts with a clay surface and enters into the interlamellar spaces of a clay. When such a molecule is brought into contact with a clay mineral there occur not only the major interactions between specific groups on the organic molecule and the active sites on the surface of the clay, but also many minor interactions may take place between different parts of the surface and the organic molecule. Competition with water molecules for the surface is also often involved in a major way.

The total change in free energy, involving the heat of adsorption plus the change in entropy, when organic molecules react with clays, is an important factor in complex formation, according to Greenland (1965). Entropy is a measure of the randomness of the system, and an increase in entropy favors adsorption. He points out that where adsorption of a large molecule leads to the release of many small ones there will be an overall entropy increase. However, the gain due to release of water molecules is partially offset by the loss of entropy due to the restriction in freedom of the adsorbed organic molecule. The extent of the offsetting effect is dependent on the shape and configuration of the organic molecule. Greenland states that "the extent to which the adsorbed molecule can collapse to the clay surface also determines the number of contacts made with the surface, and hence the total magnitude of the segment-surface interaction energies and the amount of previously adsorbed water which is displaced." The properties of the surface, organic compound, and medium in which the reaction takes place, as summarized by Greenland (1965), are shown in Table 9.II.

An excellent discussion of both the physical and biological chemistry of clay mineral–organic nitrogen complexes has been presented by McLaren and Peterson (1965). Thermodynamic considerations are considered at some length. Marshall (1964) has also discussed at some length the physicochemical properties of soil humic matter, including the interaction with soil minerals. Mortland and Wolcott (1965) have reviewed researches on the adsorption of inorganic nitrogen compounds by soil minerals.

When organic colloids are allowed to react with inorganic colloids to form complexes it is common for many or most of the reactive groups to be neutralized. This observation

TABLE 9.II

PROPERTIES OF COMPONENTS OF THE SYSTEMS THAT INFLUENCE THE ADSORPTION OF ORGANIC COMPOUNDS BY CLAYS (from GREENLAND, 1965)

Properties of surface	*Properties of organic compound*	*Properties of medium*
Extent (total surface area)	charge	those which affect its behaviour
	size	
Accessibility (size and tortuosity of pores)	polarity	(*1*) as solvent for organic compound
	polarisability	
Chemical nature of atoms forming surface (O or OH)	shape	(*2*) as competitor with organic compound for sites on clay surface
	flexibility	
Charges at surface (spatial density and distribution, origin)		
Exchangeable ions on surface		
Configuration of surface		

has been made by many investigators. De Silva and Toth (1964), for example, noted that such complexes had a lower Zeta potential than the components. During complex formation, reductions in cation exchange capacities ranged from 18 to 90% over a pH range of 5.5 to 8.5. They observed that colloid clay soils of kaolinite, bentonite, and illite did not have an isoelectric point but remained negative over a wide pH range. Organic colloids isolated from composts were amphoteric, whereas those from peat and coal humus were electronegative. These properties affect the charge on any organic–inorganic complexes that may be formed.

ADSORPTION BY VARIOUS MINERALS

Montmorillonite

The 3-layer mineral, montmorillonite, has been used to the greatest extent in studies involving the interactions of organic compounds with clay. It has a large surface area that is easily determined, a rapid rate of adsorption, a high capacity for adsorption, and a readily expandable lattice (McLaren et al., 1958). X-ray diffraction methods may be applied readily to the clay–organic matter preparations to establish the fact of adsorption, the orientation of the adsorbed molecule, and the number of layers of organic material adsorbed in the crystal lattice. Adsorption isotherms and spectroscopic data supply information that supplements the X-ray analyses.

Several studies involving the adsorption of amino compounds by montmorillonite have been reported. Amino acids are adsorbed in the cationic form and the more basic they are the greater the adsorption. The quantity so adsorbed is, according to Greenland (1965), limited by the cation-exchange capacity of the clay if the number of carbon atoms does not exceed eight, but for larger cations it is limited only by the surface area of the clay. Physical adsorption that does not involve cation exchange is also involved. Greenland states that these forces "are composed of an interaction between the dipoles of the amino acids and the exchangeable cation and charged surface sites on the clay, and of dispersion forces between the surface and the amino acid molecules." Such physical adsorption can occur at the isoelectric point of the clay where cation exchange is not involved.

Studies of the adsorption of proteins by montmorillonite (see Greenland, 1965) have also been reported. The early studies were initiated at the time when it was believed by some that much of the nitrogen in soils is there in the form of protein, and when there was no satisfactory explanation for its resistance to microbial attack. The formation of protein–clay complexes seemed to offer a possible explanation for the stability of the protein. The early work of Hendricks (1941), Ensminger and Gieseking (1939, 1941, 1942) and of Ensminger (1942) was outstanding and emphasized the importance of such complex formation. They determined many of the factors involved and demonstrated that the clay does protect protein against enzymatic hydrolysis.

It is now established that protein enters into the clay lattice and forms one, two or more layers, thereby expanding the interlamellar spacings to various degrees. The amount of protein adsorbed may be as great as 2.4 g per g of montmorillonite. Both cation exchange and physical adsorption are involved. Armstrong and Chesters (1964) state that maximum adsorption of protein by bentonite occurs at the isoelectric pH of protein, and 90% of maximum adsorption occurs within the first 3 minutes. Lattice expansion up to 64 Å was observed. At maximum adsorption they were of the opinion that two layers of protein (lysozyme) were adsorbed.

The adsorption of several carbohydrate phosphates by bentonite was studied by Goring and Bartholomew (1951). The sequence of decreasing adsorption of the salts on monovalent cations was phytin > phytin derivatives > fructose 1-6 diphosphate > fructose-6-phosphate > glucose-1-phosphate > glycerophosphoric acid > phosphoglyceric acid. Salts of divalent cations were adsorbed to a greater extent than those of monovalent cations. The carbohydrate phosphates were adsorbed to a much less extent by illite and kaolinite.

The nature of the adsorption of nucleic acid materials (mononucleotides, nucleic acids, and nucleoproteins) by clays was studied by Goring and Bartholomew (1952). The rate of reaction of ribonucleic acid with bentonite increased with temperature in the 7–45°C range and reached an equilibrium within about 24 hours. The reaction was reversible. Adsorption was greater in the presence of calcium or magnesium than in the presence of sodium or potassium, and was linearly related to cation-exchange capacity of the clay. It also decreased from pH 4 to 7 and was almost negligible above pH 8. They concluded that these organic phosphates were adsorbed through their cationic and orthophosphate groups and were at least partially adsorbed between the silicate layers of bentonite. They were also adsorbed to a lesser extent by illite and kaolinite. The studies indicate that adsorption markedly reduces the rate at which organic phosphorus is dephosphorylated.

Since the surfaces of montmorillonite are negatively-charged it is not surprising that adsorption of negatively-charged organic molecules takes place only slowly, if at all, and they are only loosely held. In explanation of the adsorption that does occur it has been suggested that exchangeable cations, such as Ca^{2+}, may act as bridges between the organic ions and the clay. There are also some indications that either aluminum, or aluminum oxides or hydroxides, sometimes act as bridges. It is possible that chelation can play an important role, but the exact mechanisms involved are not known with certainty. Hydrogen-bonding to the clay has also been suggested as a possibility.

Most simple uncharged organic compounds are adsorbed to only a slight extent. In studies with sugars Greenland (1956) observed that they were adsorbed in appreciable amounts only where the concentration was very high. Methylated sugars were adsorbed more strongly than the non-methylated, and large molecules more than the smaller ones. Many uncharged polymers are adsorbed readily and these large molecules are held so strongly that they can be displaced only with difficulty. The fact that these large molecules are held to the clay by many bonding points presumably explains in part, at least, the difficulty in their removal, especially if the large molecule is collapsed to the surface. Other rather extensive studies on factors that affect the degree of adsorption of carbohydrates and related compounds on clays have been reported by Lynch et al. (1955, 1957).

Vermiculite, illite and mica

Clays with mica-type lattices, especially vermiculite and illite, can also react with many organic compounds to form complexes in which the organic substance is held in the clay lattice. The rate of reaction with vermiculite is fairly rapid but very slow with illite and mica. Differences in behavior of these minerals has been attributed to surface area and to the density of charge on the surface.

Kaolinite and halloysite

In the two-layer clay minerals, kaolinite and halloysite, one face of the crystal consists of a silicate sheet and the other of a gibbsite (aluminum hydroxide) layer. The silicate layer ordinarily carries a positive charge but the gibbsite has no charge. Because of the positive charge, many anionic organic compounds can form peripheral complexes with the clays. Adsorption is affected by the characteristics and size of the organic molecule, by pH, by salts, and by conditions that may favor the formation of bridge linkages. Physical adsorption, as well as ionic bonding, are also involved (McLaren, 1954 a,b).

ADSORPTION OF ORGANIC MATTER IN SOILS

The above discussion of some of the main facts, mechanisms, and principles involved in the interactions between organic compounds and the chief types of clay minerals serves to emphasize the complexities involved and the deficiencies in our knowledge. In the consideration of interactions in soils it is obvious that we are even more confused, and hence less exact, for at least three major reasons. First, we are commonly not concerned with a single type of mineral but with mixtures including transformation minerals that are not always clearly defined. Second, the organic compounds include everything from recently-added undecomposed plant and animal substances to thoroughly-decomposed materials that we designate as humus. Third, the conditions in soils, unlike those in the laboratory, never remain constant. The changes in environmental conditions are attributable chiefly to variations in weather, but those brought about by man through cultivation, fertilization, liming and cropping are often far from negligible. All of these natural and man-made variations affect, if only slowly, the nature of both the clay and the soil organic matter, and hence the interaction products. Alexandrova (1960) refers to organo-mineral colloids as a complex of highly-dispersed clay minerals, humic substances, and organo-mineral compounds in a state of coalescence.

The nature and composition of soil organic matter are discussed in the preceding chapter. Broadly speaking, it consists of nonhumic and humic substances. The nonhumic substances may include at least traces of almost any compound that normally occurs in plant and animal tissues and their biological non-gaseous decomposition products. Obviously, these compounds are so heterogeneous and differ so greatly, depending on source materials and environmental conditions, that they cannot be classified except in a general way as proteins, carbohydrates, fats, waxes, resins, lignins, tannins, etc. Some of them can form rather resistant complexes, whereas others, such as simple sugars, are almost completely non-reactive. The humified material consists of humic acid, which is soluble in alkali and insoluble in acids; fulvic acid, which is soluble in both alkali and acids; and the humins that are insoluble in alkali and acids. The molecular weights of these three types of substances are believed to range between about 2,000 and 400,000 but accurate data are not available. The molecular weights are usually in the order fulvic < humic acid < humins.

Humic acids

Most of the research dealing with the adsorption of humified organic matter on clays has been with the humic acid fraction. As pointed out in the preceding chapter, the exact composition of the humic acids is not known but there is much evidence that they consist of high-molecular-weight, negatively-charged polymers, built up from amino acids and aromatic compounds. The phenolic compounds are derived both from the microbial decomposition of lignin and from microbial synthesis; the amino acids are chiefly direct synthetic products of microorganisms or degradation products of proteins synthesized by microorganisms or higher plants. Humic acids exist as comparatively rigid spherical particles that show low viscosity in aqueous solutions.

Humic acids are strongly adsorbed on negatively-charged clay particles even though the organic acid is also negatively charged. The explanation for this is known only in part. There is general agreement, based on X-ray studies, that humic acids do not enter the crystal lattice of montmorillonite. They are apparently held by positive charges on the edges of the clay, or more likely through aluminum or iron, or their oxides, present on the clay. Bridge linkages involving polyvalent cations have been suggested as playing a role; chelation is also a likely possibility. In kaolinite the silicate layer carries a positive charge, and hence humic acids are readily adsorbed on the edges of this clay. Whether mechanisms other than direct ionic linkages are involved has not been determined, but no doubt they are because kaolinite is not present in soils in a strictly pure state. Various oxides, elements of different valencies, and organic and inorganic polymers of various kinds are present.

Jung (1943) was one of the earlier workers on clay–humus complex formation. His results indicated that sesquioxides of Fe and Al play an important part in binding the humus to clays. Khan (1951) also emphasized the importance of Fe and Al that exist in the crystal lattice of clays and help to bind the humus very tightly to montmorillonite-type minerals. In a later publication Khan (1961) considered the composition of humic substances in soils and the manner in which they are bonded to the soil minerals.

Evans and Russell (1959) found that humic acid was adsorbed very rapidly by bentonite and the process was unaffected by temperature, but only a small proportion of the organic carbon was adsorbed. The extent of adsorption was Ca and Mg systems > acid systems > K and Na systems. Adsorption by kaolin in K systems was as extensive as that by bentonite, but it was much less in the acid and Ca systems. For adsorption of humic acid carbon by kaolinite the order was Ca > acid > K.

Fulvic acids

Greenland (1965) briefly summarizes the present concepts of the nature of the fulvic acids. He states that they are a heterogeneous group of substances, consisting of phenolic compounds probably similar to humic acids but of lower molecular weight, together with a group of polysaccharides and other materials, the nature of which is largely unknown. Polysaccharides, which are mixtures of several polymers, may constitute up to 30% of the fulvic acid carbon. They are believed to be large, linear, flexible molecules of high viscosity. Uronic groups are present but carboxyl groups are less abundant than in humic acids.

Studies of the adsorption of fulvic acids by clays are very limited but apparently the non-polysaccharide portion behaves much like humic acids. According to Evans and Russell (1959) the order of effectiveness of fulvic acid adsorption on bentonite was acid > Ca > Mg > K and Na systems. Only a small proportion of the fulvic acid carbon, as in the case of humic acid carbon, was adsorbed. Kaolin was also an active adsorbent, the order being acid > Ca > K, as in bentonite systems.

Soil polysaccharides have been shown to be readily adsorbed in large amounts by montmorillonite, and they can enter into the crystal lattice to form interlamellar complexes. This behavior indicates that the polysaccharides are linear, uncharged molecules of appreciable size.

Humins

These very large molecular substances, which are similar to humic acids, are adsorbed on clay and held so tightly that they cannot be removed readily, if at all, without damage to the organic substances. Little is known about the chemical nature of these compounds or their physical properties.

Extent of organic–inorganic complex formation

Several workers (Greenland, 1965) have attempted to determine the percentage of the total soil organic matter that is adsorbed on the mineral portion of soils. These investigations have been greatly handicapped by the lack of a method that will bring about a clear-cut separation of the free organic matter from the adsorbed complexed material. It is not surprising that the perfection of a suitable method presents a problem in view of the range of mechanisms by which bonding can occur. As already pointed out, some of these mechanisms result in the formation of complexes that are so stable that it is impossible to break the chemical bonds without partially destroying the organic portion of the complex. On the other hand, some of the bonds are so weak that there is considerable doubt as to whether there is a real complex or only an organic–inorganic mixture. Most success has been realized by the use of flotation methods, using a liquid that has a specific gravity less than that of the complex but greater than that of the free organic matter. This covers the specific gravity range of about 1.75–2.0, or sometimes a little higher.

Table 9.III, taken from the paper by Greenland (1965), summarizes the work reported by five groups of workers. The last column of this table shows that the percent of the total soil carbon that was combined with the clay in the 11 soils studied ranged from 51.6 to 97.8%, with an unweighted average of 73%. These values seem almost unbelievably high to one who has not been actively working in this field of research. It is only in extremely sandy soils (not shown in Table 9.III) that the proportion of the organic matter combined with the inorganic matter is less than 50%. Apparently the more thoroughly the organic matter is decomposed the greater is the tendency to form complexes with the clays. Most of this organic matter exists in the colloidal fraction of the soil but larger particles also have organic coatings.

The results of fractionation and characterization studies of naturally occurring organo-clay complexes in a B_{nt}-horizon of a black solonetz silty clay loam were reported by Arshad and Lowe (1966). This soil was predominantly montmorillonitic with relatively large amounts of kaolinite in the coarse fraction and only traces in the fine clay. The data indicated that more organic matter was associated with the coarse clay fraction than with the fine clay. The percentage of extractable organic matter increased with decrease in particle size. There was no evidence of adsorption of organic matter in the clay lattice. As

TABLE 9.III

PROPERTIES OF SOIL ORGANIC CARBON CONTAINED IN THE CLAY–ORGANIC COMPLEX (from GREENLAND, 1965)

Experiment no.	*Soils*	*Method of separation*	*Total C in soil (%)*	*C in clay–organic complex as % of total soil C*
I	rendzina	sedimentation in benzene–bromoform, s.g. 1.75	–	66.5
II	podzol	sedimentation in Toulet solution, s.g. 1.8	1.6	89.6
	chernozem		4.4	85.2
III	silt under old pasture	sedimentation in ethanol–bromoform, s.g. 2.0	2.34	77.5
IV	rendzina	"flotation sieving"	5.8	54.3
	brown earth		3.2	68.1
V	red-brown earth	ultrasonic dispersion and sedimentation in bromoform–pet. spirit, s.g. 2.0	2.23	71.5
	rendzina		5.8	68.4
	lateric red earth		1.7	97.8
	solodized solonetz		1.04	76.4
	solonized brown soil		0.58	51.6

the particle size decreased, the aliphatic structures in the clay-adsorbed humic acids became more prominent. Aromatic structures of the humic acids increased in the order of pyrophosphate humic acid, alkali humic acid, and residual humic acid. The unextractable humic acids were highly humified and aromatic in nature.

Chichester (1969) treated Chester silt loam surface soil and subsoil ultrasonically and then subjected these to particle-size separation. He found that as particle size of the inorganic–organic soil fractions decreased, total carbon and total nitrogen increased and the C/N ratios decreased. When the surface soil and subsoil samples were incubated, the percent nitrogen mineralization increased severalfold in the finer size fractions over that in the coarser ones. The data for the surface soil are shown in Fig.9.1.

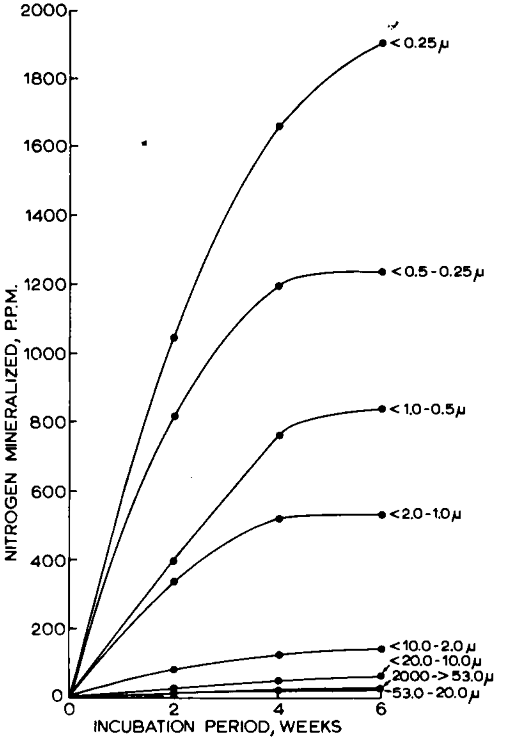

Fig.9.1. Nitrogen mineralized during incubation of water-logged Chester silt loam surface soil sedimentation size-fractions. (From Chichester, 1969.)

EFFECTS OF ORGANIC MATTER–CLAY INTERACTIONS IN SOILS

Great emphasis has over the years been placed on the maintenance of organic matter in soils. There are many reasons for this, as is clearly brought out on the pages of this book. Not the least of these are those that involve the organic–inorganic interactions that for the most part result in a soil environment that is far better than would exist if such interactions did not occur. Myers (1937) was one of the earlier workers in this field. If soil organic matter were an inert material, completely unable to interact with clay minerals, there would be far less reason for trying to maintain it. In that case many of our clay, and also very sandy, soils would no longer be suitable for agricultural use; our acreage of marginal soils would be much greater than it is now.

Chemical and physical effects

Probably the most important effects resulting from organic–inorganic interactions relate to the formation of inter-particle bonds which affect aggregate formation and swelling properties. The adsorption of the organic substances modifies the particle surface itself as well as the surface area. The binding of the organic matter to the clay particles also affects the interaction with water and with any salts present in solution.

The most obvious overall effect of organic materials is that through chemical and physical mechanisms, not yet fully understood, they help to bring about aggregate formation and aggregate stability. Aggregates serve to provide the soil porosity that permits the comparatively free movement of water, air and roots, thereby making it possible for plants to thrive. If there were no organic–inorganic interactions clay particles would tend to slump into a solid mass with very fine pores and restricted aeration. Soil aggregation and its effects are discussed more fully in Chapter 16.

Biological effects

The activities of microorganisms in soils are affected both indirectly and directly by the interaction of organic matter with clays. The indirect effects, which are usually beneficial, are exerted chiefly through the improvement in the physical condition of the soil as a result of aggregate formation. Better aeration and water relations favor the activities of the more beneficial microorganisms and repress the anaerobes. Among the direct effects may be listed the adsorption of: (1) the substrate; (2) the bacteria or their released enzymes; (3) the metabolic or decomposition products of microorganisms; and (4) organic substances added to soil.

Adsorption of substrate

The most studied example of substrate adsorption and its effect on bacterial activities is that of the entrance of proteins into the interlamellar space of montmorillonite to form complexes. Ensminger and Gieseking (1942) found that the enzymatic hydrolysis of albumen and hemoglobin was suppressed in the presence of montmorillonite but not in kaolinite. Many others have subsequently made similar observations. Proteins are not completely inaccessible to enzyme attack when present in the interlamellar regions of clays but the rate of decomposition is often markedly decreased. Some workers have reported that organic materials adsorbed on the surface of kaolinite are protected to some extent against decomposition; others have observed little or no such effect. McLaren and

Estermann (1956), for example, reported a negligible effect when chymotrypsin and trypsin were allowed to react with lysozyme adsorbed on kaolin.

Pinck et al. (1954) prepared several protein–montmorillonite complexes and studied their rates of decomposition by microorganisms. They observed that in complexes containing about 10% protein and having a c-spacing of near 15 Å, the protein was present as a monolayer between the crystal lattice sheets. In such preparations only about 20% of the protein was decomposed in four weeks. Apparently most of this represents protein that was not inside the interlamellar space; that which was inside the lattice was decomposed very slowly, as shown in Fig.9.2. Where two or more layers of proteins were present they decomposed at about the same rate as where protein alone was present without clay.

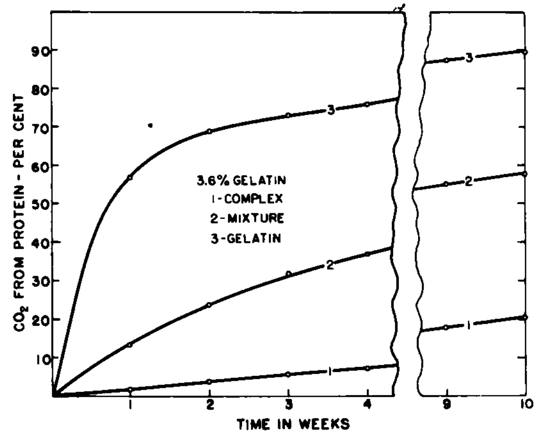

Fig.9.2. Comparative rates of decomposition of gelatin present to the extent of 3.6% in a complex with montmorillonite, in mixture with it, and alone; incubation in sand cultures. (From Pinck et al., 1954.)

Although it has been demonstrated repeatedly (Pinck et al., 1954; Lynch and Cotnoir Jr., 1956; Sen, 1961) that clay minerals, at least the 3-layer types, do exert a protective effect against decomposition by microorganisms, it is doubtful if such adsorption is of much importance in the long-time preservation of organic matter in soils, contrary to early beliefs. As pointed out in the previous chapter, proteins have not been found in more than traces in soils, nor is there much evidence for the presence of natural interlamellar organic complexes. Present evidence points to chemical composition (large, spherical phenolic-amino acid cross-linked polymers) as the primary cause of resistance to decomposition (see Chapter 8). Adsorption of substrate certainly does tend to delay decomposition in many soils but this is a comparatively short-time retardation and probably deserves little consideration as a factor in the permanence of soil organic matter over periods often as long as 3,000 years or more.

The interaction of organic matter with metals, especially aluminum and iron, to form metal–organic complexes, is still another mechanism by which organic matter resists microbial attack. In such complexes the organic matter can scarcely be considered as adsorbed on the metals or their oxides but is chemically bound to form rather resistant complexes.

Adsorption of substrate on clays sometimes speeds up its decomposition by microorganisms but the direct effects are usually not large. The addition of colloids may increase biological activities to some extent but these effects, only occasionally observed, may not be the result of adsorption phenomena but rather that of improved environmental conditions including the adsorption of inhibitory substances.

Adsorption of bacteria and their enzymes

Bacteria are adsorbed by, or adhere weakly to soils, clays, quartz sand and many other substances, especially when the medium is slightly acid and the adsorbent is well supplied with exchangeable bases (Estermann and McLaren, 1959). In general, it has been observed that the adsorbent is a less important factor in the adsorption than is the type of organism. Quantitative information on the effect of adsorption on bacterial activities is rather limited, but there is little indication that adherence of the organisms to clay minerals commonly has any marked effects on either the rate of reproduction or biochemical activities. Adherence to soil does, of course, markedly affect bacterial counts made by the plate method. Adsorbed organisms seem sometimes to be protected against unfavorable environments but whether this applies generally is not known.

When enzymes are adsorbed, the rate at which they act may be depressed because of their removal in part at least by the adsorbent (McLaren, 1954a,b; McLaren and Estermann, 1956). This effect is especially marked if they are trapped in the interlamellar spaces; the effect is usually not great when 2:1 clay minerals are not present. It is sometimes difficult to interpret experimental data because secondary effects, such as adsorption of substrate or of toxic products, may be more important than the main transformation under study.

Mortland and Gieseking (1952) found that all the clays that they studied exerted an inhibiting effect upon the enzymatic hydrolysis of organic phosphorus compounds. The effect of the clays was as follows: montmorillonite > Cisne > illite > kaolinite. The inhibition of phosphatase activity corresponded closely to the base exchange capacity of the clays, and was due primarily to their effect on the enzyme and not to adsorption of the organic phosphorus compounds by the clays.

Urease has been shown by Pinck and Allison (1961) to be completely adsorbed by hydrogen–montmorillonite and to a considerably less extent by hydrogen–kaolinite. The urease in these urease–clay complexes was less active than in the absence of clays but in the presence of urea it was gradually released from the clays and exerted its activity in solution.

Adsorption of metabolic products of microorganisms

The addition of colloidal clay to a bacterial culture may either increase or decrease the rate of growth of the microorganisms. Most of these effects relate to whether the clay makes the medium better or poorer for the organisms through its effect on inhibitory substances, oxygen supply, substrate availability, etc.

One outstanding example of the effect of adsorption of metabolic products of microorganisms is that of adsorption of antibiotics. Pinck et al. (1961a) observed that strongly basic and amphoteric antibiotics react to varying degrees to form complexes with montmorillonite, vermiculite, illite and kaolinite. Only montmorillonite adsorbed and held the acidic and neutral antibiotics, and then only in very small amounts. Strongly basic antibiotics expanded the lattice of montmorillonite by about 4.4 Å and the amphoteric ones by 7.6 Å, corresponding to monolayers and dilayers, respectively. An average of 318 mg per g of montmorillonite was adsorbed by three amphoteric antibiotics. Vermiculite adsorbed the basic and amphoteric antibiotics but to a lesser extent. Bioassay results (Pinck et al., 1961b) showed that most strongly basic antibiotics were not released from montmorillonite, vermiculite, or illite but two of them were released to varying degrees from kaolinite; the amphoteric substances were released from all of the clay minerals. When present in an agar medium, antibiotic–clay complexes did not diffuse through the agar unless a buffer was added which by an exchange reaction released the antibiotic.

Most microbiologists are of the opinion that antibiotics produced by microorganisms in soil play an important role in the ecology of the soil population (see Chapter 18). Presumably an antibiotic-producing organism can compete more effectively in an environment where hundreds of other species may be present. While this viewpoint seems logical, it has seldom if ever been proven scientifically. In fact, it is difficult to demonstrate that antibiotics are present in soils, especially in the absence of large amounts of newly-added energy sources. Soulides (1964) developed a highly sensitive method for the detection of certain antibiotics adsorbed on two different types of soil. The detected amounts per gram of soil, expressed as micrograms, were carbomycin 0.3, terramycin 0.08, and aureomycin 0.02. Adsorption on clay minerals is undoubtedly a major factor in keeping the extractable antibiotic level in soils at such a low level, but biological decomposition is also involved.

Adsorption of the decomposition products of microorganisms by colloids, especially in heavy cultures in the laboratory, may sometimes be observed. This usually favors microbial growth but a reverse effect may be encountered if the substrate or enzymes are adsorbed.

Adsorption of fertilizers and pesticides

Many organic substances, notably fertilizers, herbicides, insecticides and fungicides, are applied to soils more or less regularly. The organic fertilizers include chiefly nitrogenous materials that are decomposed readily to ammonia and present no important problems with respect to adsorption apart from fixation of the ammonium, discussed in Chapter 11. It is the pesticides that are of most interest since they are being used in ever-increasing amounts and since some of them may persist in soils for many weeks and months.

Bailey and White (1964), who reviewed the literature on adsorption and desorption of organic pesticides by soil colloids, point out that many investigators have attributed differences in bioactivity of a particular pesticide in different soils to adsorption phenomena. Adsorption affects this bioactivity to different degrees, and hence the nature and magnitude of interaction between different combinations of pesticides and soils will not always be the same.

Pesticides have been shown to react with clay minerals according to the same general pattern as do other substances discussed above. Both chemical and physical adsorption are involved. Small molecules, and larger organic molecules that are negatively charged, do not interact to any appreciable extent with moist clay minerals; positively charged materials are strongly adsorbed. Usually adsorption increases as the pH decreases but this is a function of the compound and the adsorbent.

Work with insecticides and herbicides has shown, in general, that the bioactivity of a given compound is commonly lowest in the finer-textured soils and in those high in organic matter, and highest in the coarser-textured soils. They are most readily leached from the sandy soils that are low in organic matter. These facts point to the importance of interaction with both clays and soil organic matter but of course factors other than adsorption are involved. Montmorillonite and vermiculite, which have high cation-exchange capacities and surface areas, have great capacities for adsorption due to both coulombic and van der Waals forces; the other clay minerals have much less capacity for adsorption.

Under practical conditions the amount of the various pesticides applied is so small in relation to the soil mass that it is often difficult to follow their fate after adsorption. Usually accumulation from year to year of organic pesticides is not a major factor since most of them are gradually decomposed, largely during the season of application.

REFERENCES

Alexandrova, L.N., 1960. *Trans. Int. Congr. Soil Sci., 7th, Madison, Wisc., 1960, Comm., II:* 74–81.
Armstrong, D.E. and Chesters, G., 1964. *Soil Sci.*, 98: 39–52.
Arshad, M.A. and Lowe, L.E., 1966. *Soil Sci. Soc. Am., Proc.*, 30: 731–735.
Bailey, G.W. and White, J.L., 1964. *J. Agric. Food Chem.*, 12: 324–332.
Chichester, F.W., 1969. *Soil Sci.*, 107: 356–363.
De Silva, J.A. and Toth, S.J., 1964. *Soil Sci.*, 97: 63–73.
Ensminger, L.E., 1942. *Soil Sci.*, 54: 191–197.
Ensminger, L.E. and Gieseking, J.E., 1939. *Soil Sci.*, 48: 467–473.
Ensminger, L.E. and Gieseking, J.E., 1941. *Soil Sci.*, 51: 125–132.
Ensminger, L.E. and Gieseking, J.E., 1942. *Soil Sci.*, 53: 205–209.
Estermann, E.F. and McLaren, A.D., 1959. *J. Soil Sci.*, 10: 64–78.
Evans, L.T. and Russell, E.W., 1959. *J. Soil Sci.*, 10: 119–132.
Goring C.A.I. and Bartholomew, W.V., 1951. *Soil Sci. Soc. Am., Proc.*, 15: 189–194.
Goring, C.A.I. and Bartholomew, W.V., 1952. *Soil Sci.*, 74: 149–164.
Greenland, D.J., 1956. *J. Soil Sci.*, 7: 319–334.
Greenland, D.J., 1965. *Soils Fertil.*, 28: 415–425; 521–532.
Grim, R.E., Allaway, W.H. and Cuthbert, F.L., 1947. *J. Am. Ceram. Soc.*, 30: 137–142.
Hendricks, S.B., 1941. *J. Phys. Chem.*, 45: 65–81.
Jung, E., 1943. *Bodenk. Pflanzenernähr.*, 32: 325–336.

Khan, D.V., 1951. *Dokl. Akad. Nauk S.S.S.R.*, 81: 461–464.

Khan, D.V., 1961. *Pochovedenie*, 1: 10–18.

Lynch, D.L. and Cotnoir Jr., L.J., 1956. *Soil Sci. Soc. Am., Proc.*, 20: 367–370.

Lynch, D.L., Wright, L.M. and Cotnoir Jr. L.J., 1955. *Soil Sci. Soc. Am., Proc.*, 20: 6–9.

Lynch, D.I., Wright, L.M., Hearns, E.E. and Cotnoir Jr., L.J., 1957. *Soil Sci.*, 84: 113–126.

Marshall, C.E., 1964. *The Physical Chemistry and Mineralogy of Soils.* Wiley, New York, N.Y., pp. 158–187.

McLaren, A.D., 1954a. *J. Phys. Chem.*, 58: 129–137.

McLaren, A.D., 1954b. *Soil Sci. Soc. Am., Proc.*, 18: 170–174.

McLaren, A.D. and Estermann, E.F., 1956. *Arch. Biochem. Biophys.*, 61: 158–173.

McLaren, A.D. and Peterson, G.H., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 259–284.

McLaren, A.D., Peterson, G.H. and Barshad, I., 1958. *Soil Sci. Soc. Am., Proc.*, 22: 239–244.

Mortland, M.M. and Gieseking, J.E., 1952. *Soil Sci. Soc. Am., Proc.*, 16: 10–13.

Mortland, M.M. and Wolcott, A.R., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 150–197.

Myers, H.E., 1937. *Soil Sci.*, 44: 331–359.

Pinck, L.A. and Allison, F.E., 1961. *Soil Sci.*, 91: 183–188.

Pinck, L.A., Dyal, R.S. and Allison, F.E., 1954. *Soil Sci.*, 78: 109–118.

Pinck, L.A., Holton, W.F. and Allison, F.E., 1961a. *Soil Sci.*, 91: 22–28.

Pinck, L.A., Soulides, D.A. and Allison, F.E., 1961b. *Soil Sci.*, 91: 94–99.

Russell, E.W., 1961. *Soil Conditions and Plant Growth.* Longmans Green, London, 9th ed., 688 pp.

Sen, B.C., 1961. *J. Indian Chem. Soc.*, 38: 737–740.

Soulides, D.A., 1964. *Soil Sci.*, 97: 286–289.

Talibudeen, O., 1950. *Nature*, 166: 236.

SOURCES AND POSSIBLE FATE OF NITROGEN IN MINERAL SOILS

Chapter 10

BIOLOGICAL FIXATION OF NITROGEN

INTRODUCTION

In this book on soil organic matter it may seem to some readers that a chapter on biological fixation of nitrogen is irrelevant, but the author considers that the arguments for inclusion of such a chapter greatly outweigh those for exclusion. Not only does humus contain about one part of nitrogen for every 10 parts of carbon but the nitrogen, by its effect in increasing plant growth, is to a large extent responsible for the amount of carbon that reaches the soil via photosynthesis, and hence for the level of humus in the soil.

The earth's atmosphere, approximately 80% of which consists of nitrogen gas, has over the past millions of years apparently constituted almost the sole source of nitrogen for the nutrition of all forms of life on the earth's surface. Until very recently it had been assumed that actually all of the nitrogen in soils and in fresh and salt waters came originally from the air but recent studies by Stevenson (1959) and Adams and Stevenson (1964) have shown that the undecomposed rocks of the lithosphere contain more nitrogen than is present in the whole of the earth's atmosphere (see Chapter 11). In fact, the atmospheric nitrogen may have been derived initially from the nitrogen in rocks. Although this is a matter of considerable scientific interest, as a practical matter in terms of one person's lifetime we will not err greatly if we ignore the rocks as a source of plant nitrogen, since rock disintegration, especially at lower depths, is such an extremely slow process. Certainly the nitrogen that is now in the atmosphere, regardless of its origin, is now furnishing essentially all of the new nitrogen that is being taken up by plant life in soils and oceans.

Under natural conditions in the absence of man any soil at any location tends to reach a fairly stable equilibrium with respect to both nitrogen and carbon contents. Under such conditions there is a slow release of nitrogen into the air as decomposition proceeds but there is also an uptake of nitrogen of similar magnitude from the air. The biological uptake or fixation of nitrogen may be small but the release is also small during any short interval. When man disturbs the equilibrium then the changes, particularly the losses, can be large and the fertility level (including both carbon and nitrogen) can be lowered quickly. Under conditions where combined nitrogen is not applied as fertilizer, the nitrogen-fixing symbiotic and nonsymbiotic microorganisms are a major factor in the maintenance of organic matter at some equilibrium level.

In discussions of natural sources of nitrogen gains in soils reference is always made to that brought down in rainfall. This may vary in different locations from about 1 to 20 lb.

per acre per year with an average of 5–8 lb. (Allison, 1965). At one time it was assumed that much of this nitrogen was fixed by means of electric discharges. We now know that such fixation is almost negligible; most of this rainfall nitrogen is in the form of ammonia and organic matter that came from the earth.

There is also some evidence that soils absorb ammonia from the atmosphere but this is nitrogen that was volatilized from the soil or from the burning of coal and other organic substances. The limited amount of earlier information on this subject, discussed by Allison (1965), is not very convincing. More recently, however, Malo and Purvis (1964) observed an absorption of 23–91 g atmospheric NH_3-N per acre per day (18–72 kg/ha/year) under field conditions in New Jersey. Similar experiments by Hanawalt (1969a,b) conducted in New Jersey gave average values of 55–74 kg/ha/year. Whether these values are representative of soils elsewhere remains to be determined but in any case this is not a new supply of fixed nitrogen.

Nitrogen-fixing microorganisms are commonly divided into two groups, namely, the nonsymbiotic or free-living ones, and the symbiotic organisms that live on the roots of higher plants and fix nitrogen cooperatively with them. The two groups will be considered here in that order.

NONSYMBIOTIC FIXATION OF NITROGEN

Much work has been done during the past 80 years in an effort to determine which kinds and species of soil microorganisms possess the ability to fix atmospheric nitrogen, their distribution, and the amount of nitrogen fixed under a variety of environmental conditions (Jensen, 1965). Many claims and counter-claims have been made from time to time as to the ability of a given organism to utilize free nitrogen gas. This can be attributed primarily to the limited nitrogen-fixing ability of many microorganisms and to the inadequacy of the methods used for detection of the ability. The use in recent years of ^{15}N-labeled nitrogen has settled most of the arguments and shown that nitrogen-fixing ability is indeed widespread, even if limited in amount, among microorganisms. Reference should be made to the discussions by Jensen (1965) and Alexander (1961) for details regarding the nitrogen-fixing ability of specific groups and species of microorganisms. The discussion here will deal primarily with the more important of these organisms and the ones that have received the most study. These include bacteria that live heterotrophically and blue-green algae that obtain their energy by photosynthesis. Claims have been made from time to time that certain fungi, yeasts and actinomycetes are able to use atmospheric nitrogen but there is no general agreement as to which species if any possess this faculty. If any of these organisms are nitrogen fixers the amount fixed is too small to be of much economic importance.

Heterotrophic microorganisms

The organisms involved

(1) *Aerobic bacteria.* The most interesting of the aerobic nitrogen fixers is *Azotobacter.* This genus has long been studied partly because of its large cells and unusual morphological characteristics, but also because of its comparatively high nitrogen-fixing ability in the presence of a suitable source of energy. In laboratory culture media a fixation of 10–20 mg nitrogen per gram of sugar oxidized is not uncommon, and of course a fixation of this magnitude is readily demonstrated by ordinary Kjeldahl analysis, contrary to experience with many other microorganisms.

Azotobacter is, aside from its unusual morphological features, a typical soil inhabitant although rarely present in large numbers. The most commonly found species are *A. chroococcum* and *A. beijerinckia*, although *A. vinelandii* is not uncommon. In the laboratory, *Azotobacter* is usually grown on simple sugars or mannitol in the presence of the usual mineral elements, but it is capable of utilizing a number of other low-molecular weight compounds. The presence of a few parts per million of molybdenum to serve as a catalyst is required for vigorous fixation, although vanadium acts as a less efficient substitute. There is sometimes a considerable response to traces of other elements, especially Fe, Ca and possibly B, but there is some uncertainty as to the essentiality of these elements. Apparently various species respond differently to these nutrients.

Azotobacter has the highest rate of respiration of any known living organism with QO_2 values ranging up to 4,000. Apparently much of the energy consumed constitutes wasteful consumption if considered from the standpoint of nitrogen fixation. The organism fixes more nitrogen per unit of sugar oxidized if the partial pressure of oxygen is held at near 1% instead of the usual 20%.

The optimum temperature for *Azotobacter* is approximately 30°C or slightly higher for some strains. In this respect it behaves like most soil bacteria.

The optimum reaction is usually given as around neutrality with a lower growth limitation at about pH 6.0 or slightly lower.

Closely allied to *Azotobacter* is the organism known as *Beijerinckia.* This organism is usually considered as a separate genus but others have merely considered it as a slight variation of *Azotobacter.* Its chief distinguishing feature is that it is acid-tolerant to as low as pH 3–4. It resembles *Azotobacter* very closely in nitrogen-fixing ability and in growth. It is found most commonly in tropical soils, doubtless because it can tolerate their low pH, but has been reported also in cooler climates. Red lateritic soils of the Tropics are low in calcium and high in iron and aluminum, which conditions are unfavorable for *Azotobacter.* One would expect these conditions to limit the growth of *Beijerinckia* also, but such seems not to be the case even though the explanation is not known.

(2) *Anaerobic bacteria.* The chief anaerobic nitrogen fixers found in soils belong to the genus *Clostridium.* They are widespread and present in much larger numbers than are *Azotobacter.* Since they are anaerobic, they are commonly present largely as spores in the

better-aerated soils. Recent studies (Greenwood, 1963) have, however, shown that even so-called well-aerated soils are not strictly aerobic inside of aggregates or perhaps in some cases between them. If further research supports this idea we may need to reassess our views as to the importance of these anaerobes with respect to nitrogen fixation.

The numbers of clostridia in arable, unaerated and unamended soils is commonly at least as high as 10,000 per gram and may be 10–100 times this number. In the deeper layers of soils, or when they have an excess of water, the numbers may be much higher. Jensen (1940) showed that under conditions of high moisture content clostridia may dominate the soil flora within 2 or 3 days and the vegetative cells may reach numbers of 100–600 millions per gram provided suitable energy material is present.

Clostridia can utilize a fairly wide variety of energy sources including both hexose and pentose sugars, pectic substances, polysaccharides, etc. These are not oxidized completely to carbon dioxide and water as in the case of *Azotobacter* but only partially to organic acids, hydrogen, alcohol and acetone. Thus, most of the energy is left unused in these end products.

In the older literature it was frequently stated that clostridia will fix only 2 or 3 mg nitrogen per gram of sugar used but more recent work has shown that some species are capable of fixing as much as 6–8 mg nitrogen per gram of sugar. Fixations of this magnitude are considerably lower per gram of sugar than those obtained with *Azotobacter*, but on the basis of energy utilized are higher. Jensen states that clostridia can co-exist with aerobic organisms that reduce the redox potential of the medium to a level favorable for the initiation of growth by the anaerobes. If the aerobes happen to be *Azotobacter* they can utilize the end products of anaerobic growth for nitrogen fixation. The importance of such simultaneous aerobic-anaerobic fixation is unknown but is probably of more scientific than practical interest.

Activities in the rhizosphere

It was pointed out previously (Chapter 5) that the numbers of bacteria living on plant roots, or within a millimeter or so of the roots, are often several times greater than the numbers in the soil mass at some distance from the roots. These bacteria are making use of the secretion or excretions from the roots, and also decomposing root cells and root hairs as they are released.

Largely on the basis of the earlier rhizosphere studies it was hypothesized that *Azotobacter* and possibly other nitrogen-fixing organisms should thrive in the region of the roots under conditions of low level of available soil nitrogen. Numerous studies showed, however, that *Azotobacter* were seldom present in abundance in the root zone and especially not on the root surface (Clark, 1948; Rovira, 1963). Likewise, chemical studies that were accurate enough to measure any nitrogen that might be fixed usually showed no such fixation. Any claims to the contrary are not impressive if one considers critically the procedures used in conducting both the vegetative tests and chemical analyses. The rhizosphere conditions seem to favor growth of organisms other than *Azotobacter*. When the latter organisms are added as inoculant the numbers almost invariably decrease rapidly, particularly near the root surface where the pH may be too low for them to thrive.

Although the facts as stated above were well-established prior to about 1925–1928, numerous Russian workers and a few in Germany began at about that time (Allison, 1947) to advocate the inoculation of various crops with *Azotobacter.* Several positive results were reported but the methods were such as to make the final conclusions very unimpressive. Seldom were the experiments planned so as to permit statistical analyses of the results. Likewise, the analytical data were suspect because of the usual difficulties encountered in trying to determine small gains of nitrogen in soils where tracer techniques are not used.

Using the inoculant, Azotogen, prepared in Russia, as well as pure cultures of *Azotobacter*, Allison et al. (1947) tested the efficiency on six crops grown in the greenhouse under different conditions. No significant effect of inoculation on growth or on nitrogen fixation was observed. Clark (1948) tested the Russian preparation on tomato seedlings and observed a rapid decline in numbers after inoculation, and the decline was greater in cropped than in uncropped soils. Inoculation with *A. chroococcum, A. vinelandii,* and Azotogen did not alter the microflora of tomato roots. The *Azotobacter* flora of soil that normally contained these bacteria was no greater where tomatoes, soybeans, broccoli or mustard were grown than in uncropped soil. These results are representative of essentially all tests of this type that have been made in western Europe and in the United States (Jensen, 1965).

The enthusiasm for the use of Azotogen in the U.S.S.R. has apparently decreased markedly in recent years and less emphasis seems to be placed on the subject now. Even those workers in the U.S.S.R. who have claimed positive results have not been too certain that the benefits were due to nitrogen fixation. Sometimes the benefits claimed have been attributed to growth stimulation by auxins, hormones, vitamins and other substances released from the growing plant roots.

The conclusion must be that there is no good reason at present to expect that any appreciable gain in nitrogen can be expected from inoculation of crops with *Azotobacter*. Not only is there no proof of such benefits but if *Azotobacter* were capable of thriving in the rhizosphere it would already be there in numbers. We know that this organism is a poor competitor because of pH limitations and limited energy sources in the soil that it can utilize. Very little research has been reported concerning the activities of other nitrogen-fixing bacteria in the rhizosphere but there are few reasons for believing that such fixation is very important.

Associative action between nitrogen fixers and other microorganisms

The chief sources of energy in soils are cellulose, hemicellulose, and lignin, none of which is directly available for use by nitrogen-fixing bacteria. Any appreciable nitrogen fixation on these substances by the heterotrophic nitrogen fixers must therefore be brought about with the aid of other soil organisms (bacteria, fungi, and actinomycetes) that are capable of decomposing one or more of these three types of substances. In the process, and under certain conditions, some of the breakdown products may be assimilated by nitrogen-fixing microorganisms growing in association with the others. In the soil the compounds that are likely to be released are alcohols, organic acids, aldehydes, etc. that are products of fermentation. Although aerobic nitrogen-fixing organisms can utilize many of these substances, it is doubtful if they actually benefit much from them in soils because of the keen competition with other soil organisms, many of which can grow more rapidly, and under conditions that these nitrogen fixers cannot tolerate.

The matter of oxygen supply is crucial. The incompletely dissociated energy sources are formed only under anaerobic, or near-anaerobic conditions, whereas the nitrogen-fixing organisms that can utilize them must have oxygen. Any appreciable fixation by aerobic bacteria through such cooperation would, therefore, seem possible in soils only where anaerobic pockets exist in close proximity to aerobic areas, or else where there are frequent alterations of aerobic and anaerobic conditions throughout the soil. This latter condition would be expected only in the heavier soils and even then not at very frequent intervals.

The carbon-containing constituents, mentioned above, that are potential energy sources for nonsymbiotic nitrogen-fixing organisms living in soil, always occur as plant products in various stages of decomposition, and hence in association with nitrogen. Since the amount of nitrogen fixed by these microorganisms is likely to be inversely correlated with the amount of available nitrogen present, it follows that the presence of this fixed nitrogen can and does markedly curtail nitrogen fixation. It has been shown repeatedly that microorganisms almost invariably use available fixed nitrogen in preference to free nitrogen gas even though they seem to grow almost equally well on either when present as the sole source.

Jensen (1965) gives an excellent review of the present status of our knowledge of the utilization of energy sources for nitrogen fixation. With regard to cellulose he states that "there is little evidence of nitrogen fixation by the azotobacter in association with the important aerobic soil inhabitants *Sporocytophaga* and *Cytophaga* that decompose cellulose via oligocelluloses, cellobiose, and glucose and are largely restricted to utilization of this class of compounds. The carbon sources are dissimilated oxidatively with formation of no other organic by-products than small amounts of acetic acid; a mucilage of polysaccharide- or polyuronide-like character is synthesized. Azotobacter may multiply to some extent in association with the cytophagas, but the gains of nitrogen are nil or scarcely significant." In studies where other aerobic bacteria, and also fungi and actinomycetes, have been cultured on cellulose there was negligible fixation by *Azotobacter* present in the cultures.

The results given above for aerobic cellulose-decomposing organisms do not always apply to facultative-aerobic cellulose decomposers. Jensen and Swaby (1941), for example, reported that combinations of pure cultures of various species of *Azotobacter* and cellulose-decomposing *Corynebacteria* can fix about 6–14 mg N per g of cellulose decomposed. Filter paper, grass and straw were all utilized. Crude xylan, a hemicellulose, was also utilized efficiently. The authors state that nitrogen fixation of this magnitude was obtained only when the cellulosic material was submerged in liquid media; under completely aerobic conditions the fixation was almost negligible. When grown in the filtrates of the cellulose-cultures of *Corynebacteria*, *Azotobacter* fixed as much as 5.7 mg N per g of cellulose decomposed. In deep cultures of the two organisms the oxidation-reduction potential reached a considerably lower level than in pure cultures of the *Corynebacteria*.

There is some slight evidence that clostridia can fix nitrogen when growing in association with aerobic cellulose decomposers but such an association would not be expected, except possibly where there are anaerobic pockets in an otherwise aerobic soil, or where alterations of aerobic and anaerobic conditions occur. Such fixation in soils is probably negligible.

Hemicelluloses are also a possible source of energy for nitrogen fixation by the clostridia that can utilize xylose and other substances released from them. There is little evidence for such fixation, and even less evidence that lignin plays a role in biological nitrogen fixation.

Claims have also been made from time to time that nitrogen-fixing bacteria can grow in association with Chlorophyceae (green algae) using the carbohydrates synthesized by the alga. There is little evidence for such claims. The algae not only show little tendency to liberate carbohydrates but in soil grow only at the surface where conditions are not very favorable for bacteria. The early claims of associative action were usually observed in impure cultures when nitrogen-fixing Cyanophyceae (blue-green algae) may have been present.

Fixation in Temperate Zone

In the early years of the present century many papers were published that reported the quantities of nitrogen fixed in soils under laboratory conditions although occasionally field soils were sampled. Any gains of nitrogen were usually determined by the Kjeldahl method. Where 1–5% of sugar or mannitol was added, as was the common practice, fixations up to 10–20 mg nitrogen per 100 g soil were sometimes observed. Where no such additions were made, or where crop residues served as the energy source, the quantity of nitrogen fixed was negligible, or at least well within the experimental error involved in soil sampling plus chemical analysis. Under the more carefully conducted experimental conditions in the laboratory the sum of these two errors normally amounts to at least 1 or 2 mg nitrogen per 100 g soil, which is the equivalent of 20–40 lb. per acre of 2,000,000 lb. of soil. In field studies the sampling error is much greater than this. It follows, then, that none of these older data obtained by these methods is of any value in showing the amount of nitrogen fixed annually by nonsymbiotic microorganisms under field conditions. Estimates were often made that such fixation amounts to 5–40 lb. per acre per year but these were largely guesses based on our knowledge of the physiology of the bacteria, on long-time soil fertility experiments, and on agronomic observations rather than on chemical analysis of short-time experiments.

The development of the tracer technique using ^{15}N has made possible the securing of more accurate nitrogen fixation data, since under laboratory conditions this method is reported to be sufficiently accurate for the detection of 0.1–0.2 mg nitrogen per 100 g of soil. Unfortunately, I know of only one published paper that has made use of this excellent technique; this was the work of Delwiche and Wijler (1956). Using ^{15}N-labeled nitrogen gas in vessels containing soil, they reported a fixation of up to 40 lb. of nitrogen per acre when glucose or sucrose was added. Only slight fixation was obtained when grass, straw or alfalfa was the energy source. In grass sods a fixation of 12 lb. per acre occurred. Additional data of this type are much needed.

In recent years an occasional paper has reported fixations in grass sods under field conditions of 50–100 lb. of nitrogen per acre per year. It is reasonable to suppose that such an environment should favor nonsymbiotic fixation but until more such data are reported that have been obtained from experiments that have been conducted with extreme care it is well to withhold acceptance of these high values. In such experiments there are many sources of error, among which are soil sampling, the presence of unsuspected legume plants, animal contamination in pastures, and leaching from higher levels. Furthermore, if such fixation does occur, we still can only wonder as to how much of it is attributable to nitrogen-fixing blue-green algae rather than to nitrogen-fixing bacteria.

Present information, then, seems to lead to the conclusion that nonsymbiotic bacterial fixation in cultivated soils of the Temperate Zone can almost be ignored for all practical purposes in short-time cropping experiments. This may not be true in many uncultivated soils, such as the chernozems that developed over many centuries. The annual additions of nitrogen to these soils before they were cultivated was probably much greater than to cultivated soils. The yearly return of plant residues furnished a source of energy that indirectly contributed much to the soil nitrogen level even if the energy sources were used wastefully. Under permanent plant cover the nitrogen losses were negligible and any gains could accumulate, first as plant tops and roots and ultimately as soil organic matter. But here, again, we must refrain from attributing all the gains to nonsymbiotic nitrogen-fixing organisms. At least a little nitrogen was fixed in the atmosphere or was absorbed as ammonia from the air, and furthermore, nitrogen-fixing legumes are almost ubiquitous in nature, and even nitrogen-fixing blue-green algae are not a rarity.

Moore (1966) has given an excellent summary of our information on nonsymbiotic nitrogen fixation and presented data showing the reported gains obtained by various workers. He concludes that regardless of faulty experimental techniques, lack of statistical control, and inherent errors, "sufficient reliable data are available to suggest that non-symbiotic fixation may be of a magnitude to be of agronomic significance under some circumstances." He states further that "it is reasonable to hypothesize that nitrogen gains in soil are the result of the cumulative action of numerous microorganisms fixing small quantities of nitrogen and that the role played by Azotobacter is insignificant in most cases." These statements presumably include the contributions of nitrogen made by blue-green algae, since he includes them in his discussion.

Fixation in the Tropics

Our knowledge of the importance of free-living nitrogen-fixing organisms in the Tropics is more uncertain than for the Temperate Zone, and is based more on the observations of scientists working in the region than on accurate analytical data. According to Meiklejohn (1962), nitrogen-fixing microorganisms are abundant in certain tropical regions where the rainfall is 60–300 inches per year, and they are apparently contributing much nitrogen to the native vegetation. It seems that plants in this region show signs of having abundant nitrogen even though the soil content is low. Nye and Greenland (1960) also state that poor soils in Africa will support a luxuriant forest growth, and that fertilizer experiments conducted in moist evergreen and semi-deciduous zones show that plant growth is not limited by the natural nitrogen supply.

Shifting cultivation is a system practiced in the Tropics. This involves the cutting and burning of trees, followed by the growing of mixed annual and perennial crops for 2 or 3 years. As the soil becomes too poor to grow good crops it is allowed to return to brush and trees; after 10 to 20 years these are cut and the cycle is repeated. Abandoned land returns after a few years to near its previous state of fertility and the native vegetation flourishes. There is strong circumstantial evidence for high biological nitrogen fixation under shifting culture and Nye and Greenland state that the fixation may be even greater where the forest is not disturbed. We must not hasten to attribute this fixation entirely to nonsymbiotic microorganisms because many forest species are legumes, although it is often stated that they are usually devoid of nodules. Proof of this statement is very much needed. It seems highly improbable to me that all of the native legume tree species are unable to fix nitrogen. We at least know that the nonlegume *Casuarina,* found in warm climates, is commonly well nodulated and an active fixer of nitrogen. It was introduced many years ago into the southern half of Florida and can now be seen in many places growing luxuriantly in soils that are so sandy and devoid of nitrogen that few other nonlegumes can do more than merely exist.

Nye and Greenland (1960) have made extensive studies of the nitrogen problem in Africa and have calculated from analytical data on soils and vegetation that the yearly fixation is of the order of 95 lb. of nitrogen per acre, or even higher if leaching or gaseous losses are appreciable. Where savanna vegetation prevails the annual fixation is estimated to be about 35 lb. Greenland (1959) estimated that under tropical conditions the net annual gains of nitrogen are in the range of 50–150 lb. per acre under forest and 40–120 lb. under savanna conditions. Since legume weeds are unlikely to be present under savanna conditions, such nitrogen gains would necessarily be the product of nonsymbiotic microorganisms. Nye and Greenland also refer to the work of Beirnaert who estimated that in the forests of the Central Congo Basin the annual fixation is about 90 lb. of nitrogen per acre.

The observations of Ruinen (1956, 1961, 1965) may throw light on this nitrogen accretion problem. She states that the nitrogen-fixing bacterium, *Beijerinckia,* abounds on the moist leaves of tropical vegetation in Indonesia and Surinam. These sticky leaves in rain forests can doubtless supply an abundance of energy material that the bacteria may utilize in nitrogen fixation. Until more data are available we can only guess as to whether nonsymbiotic bacteria or legume nodules are the main source of the apparently abundant nitrogen supply found in the Tropics.

Mention should also be made of the report by Vasantharajan and Bhat (1968) to the effect that mulberry leaves harbor populations of microorganisms, including *Azotobacter* and *Beijerinckia.* Plants grown under aseptic conditions showed increased growth and nitrogen content following inoculation of the leaf or root with *Azotobacter*. Further research is needed before proper evaluation of this work can be made.

Autotrophic microorganisms

The autotrophic nitrogen-fixing microorganisms that are of primary interest as soil and water inhabitants are the blue-green algae. These organisms can grow normally, even if at a comparatively slow rate, on a liquid medium containing the usual mineral elements without fixed nitrogen or carbohydrate if sunlight or other suitable light source is provided. They obtain their energy supply via photosynthesis and hence require a supply of carbon dioxide. If available fixed nitrogen is added to the medium they will utilize it, as do other nitrogen-fixing microorganisms, but growth is usually little accelerated by such additions. Since their growth requirements are so simple, these algae are likely to be found growing in nature where nutrient conditions are unsuitable for other organisms provided that moisture is not limiting.

The proof that certain species of blue-green algae can utilize atmospheric nitrogen was not realized until 1928. Prior to that it had been shown that mixed cultures of algae and bacteria sometimes fixed nitrogen but most workers were inclined to attribute the fixation to the bacteria that were supposedly living cooperatively with green or blue-green algae. Most blue-green algae are surrounded by a gelatinous secretion in which bacteria thrive, making it very difficult to obtain bacterial-free cultures.

Drewes (1928) was the first to present proof that certain blue-green algae can utilize free nitrogen gas although Pringsheim had at a much earlier date succeeded in obtaining bacterial-free cultures of some of these organisms. Drewes grew *Anabaena variabilis, Nostoc punctiforme* and another species of *Anabaena* in pure culture and obtained about 2–3 mg N fixed per 250 ml of nitrogen-free medium during a period of two months.

Allison and Morris (1930), working independently of Drewes, succeeded in obtaining a pure culture of a blue-green algae that they isolated from soil. It was tentatively identified as *Anabaena variabilis* but later work showed that it was *Nostoc muscorum*. This organism fixed as much as 10 mg N in 45 days and 18 mg in 85 days per 100 ml of medium containing no carbohydrate, when grown under artificial light of an intensity of 200–300 ft. candles (Allison et al., 1937). The lower and upper pH limits of growth were approximately 5.7 and 9.0, respectively, with an optimum in the range of 7.0–8.5. Since the publication of these early papers numerous other bacterial-free Cyanophyceae have been obtained by various workers and shown to fix atmospheric nitrogen, but it should be emphasized that not all blue-green algae are nitrogen fixers.

The growth requirements of these nitrogen fixers, as well as their slow growth rate, shows that it is unlikely that they contribute much nitrogen to cultivated soils. They are confined almost wholly to the soil surface where light is available, but at this location moisture is so limited that growth is almost impossible. Also cultivation disturbs any growth that they may be able to make. There are indications, however, that in grasslands or in dark moist places they may add appreciable amounts of nitrogen to the soil. Their ability to grow under low light intensities would favor such fixation. In this connection it is interesting to note that Cameron and Fuller (1960) demonstrated that algal and lichen crusts taken from the surface of semi-arid Arizona soils contain nitrogen-fixing blue-green algae. When these crusts were incubated in the laboratory in illuminated moist chambers for 4 weeks, nitrogen gains of 0.024–0.04% (240–400 p.p.m.) were found. Under natural semi-arid conditions presumably the algae would be present largely or wholly as spores, and since a few days are required after a rain for vegetative cells or filaments to develop, the quantity of nitrogen fixed per year under natural conditions where rains are infrequent would probably be negligible. It is, however, amazing that the algae should even be present in such an environment.

It is in rice paddies, or other frequently submerged lands, that nitrogen-fixing algae are believed to be a very important factor in agriculture. Much work has been done in this area in recent years but we are still uncertain as to the amount of nitrogen fixed under field conditions (MacRae and Castro, 1967). De and Mandal (1956) estimated a fixation of up to 44 lb. of nitrogen per acre per year. Under many conditions it seems that the nitrogen fixed by algae is the main source of this element for the rice crop, but it is well not to overstress the importance of these organisms. Some studies have shown that for unknown reasons, nitrogen-fixing species are not always present in rice paddies.

These algae are also reported to be an important factor in the increase of fixed nitrogen in lakes (Dugdale and Neess, 1961; Stewart et al., 1967; Howard et al., 1970). Such fixation would usually be considered as objectionable since nitrogen serves as a pollutant and increases the growth of all kinds of plant life, which on death tend to produce an odorous, oxygen-deficient medium unsuitable for fish, or for human recreation.

Photosynthetic bacteria that fix nitrogen are also known to exist in nature but their growth characteristics seem to make certain that they are of negligible economic importance. These anaerobes are of considerable scientific interest because of their unique metabolism and growth characteristics.

SYMBIOTIC FIXATION OF NITROGEN BY LEGUMES

Nitrogen fixation as a result of a symbiotic relationship between certain microorganisms and higher plants occurs in both legumes and nonlegumes, but it is only in the legumes that such fixation ordinarily plays a major role in agriculture. Symbiotic nitrogen fixation is commonly of such magnitude as to make the inclusion of a legume in the rotation of first importance if other sources of nitrogen are not available or are inadequate. This contrasts sharply with the facts as stated above to the effect that nonsymbiotic fixation in cultivated soils is usually too small for measurement by ordinary chemical methods.

Occurrence of nodules

The growing of leguminous crops, as already stated elsewhere, dates back to early historic times in Mesopotamia and Egypt. They were in common use in Biblical times. Fred et al. (1932) state that vetches, alfalfa and peas were raised in early Babylonian times. Likewise, in Egypt from the earliest historic times the seeds of the Leguminosae formed part of the food supply and entered into religious observances. The legumes used were believed to include beans, lentils, chick pea and possibly bitter vetch.

The Leguminosae constitute a large family of about 13,000 species of which only a mere two percent are cultivated. The nodulating habit among legumes is widespread, and only a few genera are known never to have nodules. Allen and Allen (1959) reported that of the 1,285 species (10%) that had been examined, 86% were nodulated. Since the large majority of legumes are found growing as weeds and in waste places, or as trees, our knowledge of the extent of nodulation is meager. Examination of the roots of these non-cultivated plants for nodules often shows their absence. This seems to be especially true of legume trees. Failure to find nodules on a given plant at any one time does not of course prove that the plant is always non-nodulated; many plants must be examined over the year if the results are to have much meaning, and this has not been done for most of the wild legumes. Occasionally a strain of cultivated crops, including soybean and red clover, fails to form nodules for reasons not fully understood. Genetic factors appear to be involved in some cases and bacterial strains in others.

Nodule formation and development

Legume nodule bacteria usually enter the plant root through the root hairs. The first evidence of this is a curling of the root hair, which is thought to be caused primarily by β-indoleacetic acid, secreted by the bacteria. Only a small percentage of the root hairs show curling and not all that curl develop nodules. After entrance, the bacteria move through an infection thread into the tissues of the host, where a rapid multiplication of the plant cells occurs. The bacteria are released into the cytoplasm and multiply rapidly for a short time. Meanwhile, the host builds a surrounding layer of cells in which an extensive vascular system is formed. The bacteria, after the initial rapid multiplication, are soon converted into non-motile, non-growing cells, called bacteroids, that in many respects give the appearance of being spore-like although they are not spores. They are commonly swollen and irregular in shape, possibly as a result of contact with alkaloids and other products of the host. Although there is no evidence that the bacteroids alone are able to fix nitrogen, it is well-established that the development of this morphological state is essential for nitrogen fixation to occur.

The size, shape, and location of nodules on legumes varies markedly in different genera and species, and also to a limited extent with the bacterial strain. Plants with taproots, such as soybeans and cowpeas, have comparatively large but limited numbers of nodules, whereas plants with very branched roots usually have smaller nodules and more of them. As soon as the first nodules begin to form, root hair infection declines and thus widespread nodulation is curtailed. In most species nodules tend to remain in a near nongrowing condition, but active in nitrogen fixation, so long as the host plant is growing normally. However, there are marked exceptions to this general statement. The author has, for example, noted that during a dry period of perhaps three weeks practically all of the nodules disappeared from the roots of soybean plants growing under field conditions. New nodules formed quickly following a heavy rain. Apparently nature attempts to maintain a balance between total plant tissue and effective nodule tissue, and as this balance is disturbed by the loss or disintegration of a nodule (for whatever reason) new nodules can take the place of the old ones.

Effective and ineffective strains of bacteria

The nodules produced by different strains of bacteria may vary widely in their ability to fix nitrogen, and this is independent of the ability of the bacteria to enter the root and stimulate the host to produce nodules. This variation in effectiveness appears to be a genetic characteristic of the microorganisms but beyond this there is great uncertainty as to the basic causes for the failure of the host plant to produce normal effective nodules.

Ineffectiveness often involves cross-inoculation groups; strains of bacteria that produce effective nodules on some plant species may produce ineffective nodules on other species. A single plant may be infected with both good and bad strains and in this case the poor strains may act as partial inhibitors of nitrogen fixation. Ineffective nodules usually develop little or no bacteroid tissue, and the growth of the meristematic tissue at the tip of the nodule may be markedly curtailed. The most distinctive feature of ineffectiveness is the absence of hemoglobin which is believed to play an important part in the biochemical nitrogen fixation process.

A characteristic of nodules produced by effective strains is that on most plants they are located near the crown of the plant and on the main roots. In soybeans and cowpeas they tend to cluster within the upper two inches of the root system and along the main taproot. The same tendency is exhibited to a somewhat lesser extent in plants, such as red clover, that have a more branched root system. Effective nodules are likely to have a weight 5–10 times greater than ineffective nodules on the same plant species.

Inoculation

The inoculation of the seeds of legumes at the time of planting or shortly before is a generally recommended procedure under the following conditions: (1) when the legume has not been grown on the soil previously, or at least not recently; (2) when there is doubt as to whether there are enough bacteria in the soil to bring about nodulation; and (3) when the bacteria already in the soil consist chiefly of ineffective strains. Since there is likely to be great doubt as to the abundance and effectiveness of the bacteria already present in the soil, inoculation is generally advisable unless the results of previous years seem to make inoculation of doubtful value. The cost of inoculants is so little that the operation constitutes cheap insurance against poor nodulation and limited nitrogen fixation. This is true in the more advanced countries. In the others, inoculation may be almost impossible because of lack of commercial inoculants for the particular legumes being grown. Serious attempts are being made to eliminate this deficiency where inoculation is so important.

Successful inoculation depends upon the use of bacterial strains that have been selected for high nitrogen-fixing ability under a wide range of field conditions. It is especially important that they be able to compete satisfactorily with ineffective strains already present in the soil. Strain selection involves repeated greenhouse and field tests under different conditions, and is further complicated by the occasional failure of effective strains to maintain their effectiveness. Sometimes several effective strains are mixed in the same culture but this introduces the possible hazard that some of these may actually be ineffective on certain host plants.

The usual legume inoculant now in use consists of finely-ground neutral sedge peat to which the bacteria have been added from liquid cultures. Years of research have shown that peat is an ideal medium in which to keep the bacteria in good viable condition for several months under commercial handling conditions.

Burton (1959) states that there are 25 cross-inoculation groups, but only 8 of these are of commercial importance. These are the alfalfa, clover, pea, bean, lupine, soybean, cowpea and lotus groups. Rhizobia cultures are available for other groups but are prepared only as needed. Burton estimates that approximately 42% of the legume seeds planted each year in the United States are inoculated. About 68% of the total inoculant produced is for soybeans, 19% for alfalfa and clovers, and 12% for all other legume seeds.

In recent years much interest has been shown in pre-inoculation, which consists in the inoculation of the seed several weeks or months in advance of its intended use. This simplifies the matter of planting when time is so important, and when the inexperienced farmer is likely not to make the extra effort to obtain and use viable peat cultures. Unfortunately, numerous tests have shown that pre-inoculation is a very questionable practice because the organisms die off very rapidly after addition to the seed.

Legume bacteria are usually sufficiently tolerant of unfavorable soil conditions to be able to persist under most conditions that the host plant can endure. However, the bacteria prefer a neutral medium and hence liming the soil where needed is often advisable both for the growth of the plant for the persistence of the bacteria in the soil. Experience has shown that good inoculation requires not just one bacterial cell per seed but several, and hence a good soil environment for bacterial persistence and multiplication is important.

Site of nitrogen fixation

Nitrogen fixation occurs in the legume root nodule, and the combined nitrogen then moves through the well-developed vascular system that is characteristic of effective nodules into all parts of the plant. For many years it was commonly stated that the fixation is probably brought about by the bacteroids located in the center of the nodules. This belief persisted even though no one had been able to demonstrate fixation either by vegetative cultures of the bacteria or by the non-growing bacteroids removed from the nodules. It seemed logical to assume that the organisms were the causative agent since so many nonsymbiotic bacteria possess this ability.

The use of ^{15}N-N as a tracer has thrown some new light on the problem but it is still far from solved. Such experiments have shown that excised nodules will fix very small amounts of nitrogen, but such fixation continues for only a few hours even though the nodules are suspended in a complete nutrient medium. It seems that a normally-functioning plant that continually supplies the nodular tissue with substances required in the fixation process is essential. At least, no one has been able to find a replacement for these plant juices. The attached nodule also continually removes the end product of fixation but such removal is of secondary importance.

A limited number of comparatively recent experiments, using ^{15}N, has indicated that the first products of fixation occur not in the bacteroids but rather in the plant tissues and cytoplasm immediately surrounding the bacteroids. Since fixation can occur only when bacteroid tissue is present and attached to the whole plant, it is obvious that fixation is a truly symbiotic process. Much more biochemical work will be needed to work out the details of the process. The progress made in recent years in the study of the mechanism of nitrogen fixation in nonsymbiotic fixation will doubtless help materially in the solution of the symbiotic fixation puzzle.

Factors affecting nitrogen fixation

Since the amount of nitrogen fixed by legumes is an important factor in determining the amount of soil organic matter formed, its persistence, and its role in crop production, it is well to consider some of the more important factors that influence fixation.

Thriftiness of host plant

Under conditions of low levels of nitrogen in soil, the amount of nitrogen fixed by effective legume nodules is closely correlated with the dry weight of the legume tissues produced. When one has said this, he has in a sense covered in a general way all of the factors involved in the fixation process. With minor exceptions, legumes fix nitrogen only as they need it and only to the extent that they use it in the synthesis of tissues. This means that fixation can be curtailed markedly by such factors as inadequate soil moisture, too low or too high a temperature, insects, plant diseases, toxic materials, a poor soil or one unsuited to the crop being grown, poor crop variety, excess acidity, poor aeration, etc. In a practical sense, then, plant thriftiness is as important, or more so, as the effectiveness of the bacterial strain and what happens to the organisms inside the root tissues. Environmental factors not only affect the growth of the plant but also the bacteria in the soil, their ability to form normal nodules, and the functioning of the nodule that they help to form.

Fast-growing plants of any given species usually have narrower carbon–nitrogen ratios than do the slower-growing ones. This may be due to the fact that photosynthesis proceeds more rapidly in slow-growing plants than tissue proliferation occurs, and carbohydrates tend to accumulate. The ratio also tends to widen as plants become older. With increase in age the rate of growth after a time slows down, starch may accumulate, and seed production takes place. In all these situations the fixation process usually slows down correspondingly. The percent nitrogen in the nodule and the rate of fixation decrease with age. There is an automatic adjustment; nature usually provides the amount of nitrogen needed and no more. In green manuring, and other cropping systems where nitrogen fixation is so important, the selection of a fast-growing, high-yielding crop may result in fixations two to five times greater than would be obtained with legumes that are slow-growing and low-yielding.

Extent of nodulation with effective bacteria

The matter of effective and ineffective strains is considered above but in a discussion of the factors that affect nitrogen fixation the subject must be mentioned again. Without nodules there is no fixation and, likewise, if only ineffective strains are present the fixation can also be zero or nearly so. With effective strains the fixation is ordinarily sufficiently high to meet the full needs of the host plant. When both good and poor strains are present the quantity of nitrogen fixed is commonly somewhat below the maximum and may be so inadequate that plant growth is markedly curtailed. These facts present a challenge for the maker of legume inoculants because the naturally-occurring legume bacteria in soil are rarely the most effective for the legume being grown. Inoculation with better nitrogen-fixing strains can markedly increase crop growth but this does not always happen. The introduced strains must be highly infective and competitive, and hopefully, able to dominate the root system.

Sometimes, even when effective bacterial strains are present, maximum fixation is not realized because of inadequate bacteria present. Apparently inoculation potential, a term used by plant pathologists, applies here. It seems that a single bacterium is less apt to gain entrance into a root than are several. An adequate inoculum potential may be realized through control of the quantity of inoculum added, or through multiplication of organisms on the root. Fortunately, however, the quantity of nitrogen fixed is not necessarily directly related to the number of effective nodules present. It is a common observation that if only a very few are present these few may become abnormally large and super-effective in nitrogen fixation.

Carbohydrate supply

Good nodulation is dependent upon a good rate of photosynthesis, or in other words on adequate carbohydrate. This explains why nodulation and nitrogen fixation are likely to be much more limited during the winter in the greenhouse than during the summer months. The same observation can be made in growth chambers by variation in light intensity.

The growth of a plant, whether legume or nonlegume, in a soil that is well supplied with nitrogen is controlled to a major extent by the rate of photosynthesis. As carbohydrate is formed, it combines with nitrogen to build up proteins and the other constituents of plant tissues. As the carbohydrate is thus utilized more is being formed and this continues as long as growth continues. Even if fixed nitrogen is present in excess, little of it is used except in combination with the carbohydrates. Much of the process of tissue formation occurs in the tops of the plants, and in the presence of adequate nitrogen the top–root ratio tends to widen. Conversely, when the nitrogen supply is so limited that there is not enough to combine with the carbohydrate to form tissues, the top–root ratio narrows and carbohydrate in the form of starch accumulates.

Essentially the same principles prevail when the nitrogen is obtained from legume nodules. Since nodulation is controlled largely by carbohydrate supply, a slightly higher level of carbohydrate may be required for good nodulation and plant growth than would be observed in more succulent plants supplied with abundant fixed nitrogen. The bacteria, or perhaps we should say the nodules, require a certain amount of carbohydrate before nitrogen can be fixed. Whether this energy supply is required for fixation or is merely needed for construction of nodules and other tissues is not known, but presumably the latter is the case.

Much has been said in the past about the importance of the carbohydrate–nitrogen relationship in symbiosis, whatever that means. Certainly, the amount of nitrogen obtained as fixed nitrogen from the soil does influence nitrogen fixation, but in the final analysis it is not some hypothetical carbon–nitrogen ratio in the plant that is of first importance; carbohydrate is the major controlling substance, the level of which fluctuates with the amount of nitrogen available to the plant (Allison, 1935).

Let us consider the carbohydrate–nitrogen interrelations further under some well-defined conditions: (1) in non-nodulated plants where fixed nitrogen is present in adequate but not excessive amounts, there is general agreement that the rate and amount of growth are controlled by the amount of carbohydrate synthesized (photosynthesis); (2) in a well-nodulated plant, as the supply of fixed nitrogen is increased the fixation of nitrogen decreases correspondingly until at higher nitrogen levels little or no nitrogen is fixed, and the nodules may nearly disappear. At this point where nitrogen fixation is not occurring, the rate of growth is also obviously dependent upon the rate of carbohydrate synthesis just as where no nodules are present; (3) at lower levels of added fixed nitrogen, where fixation is curtailed but not prevented, the amount of nitrogen fixed is determined by total carbohydrate photosynthesized minus the amount that combines with the added fixed nitrogen to form plant tissue; and (4) where effective nodules and little fixed nitrogen are present the nodules work efficiently and supply the plant with as much, or nearly as much, nitrogen as it needs, and the needs are directly correlated with photosynthesis. Therefore, whether the nitrogen in optimum amounts is obtained from fixed nitrogen in the soil or from the air via nodules would seem to make no appreciable difference; in both cases plant growth, and nitrogen fixation, where it can occur, are similarly determined by the available carbohydrate supply. Perhaps it is time to discard the carbohydrate–nitrogen relationship concept as it has been expounded in the past.

Mineral elements

Nitrogen fixation in well-inoculated legumes is, as already stated, directly correlated with total plant growth if there is little or no fixed nitrogen present in the soil. It follows, then, that a deficiency of any of the major nutrients other than nitrogen, and of the minor elements required for normal plant growth (see Chapter 14), will result in sub-optimal nitrogen fixation. Some of the major elements, particularly calcium and magnesium, not only are essential nutrients but also serve as neutralizers of soil acidity and thus play an important secondary role in nitrogen fixation.

Molybdenum is one of the elements that plays a more specific role in nitrogen fixation, both in nonsymbiotic and in symbiotic organisms. The literature with respect to legumes is reviewed briefly by Vincent (1965). Molybdenum apparently acts as a catalyst in the fixation process and tends to accumulate in effective legume nodules. Since it is a trace element, the amount required as an application to field soils may be no more than a few ounces per acre. It has been shown that 10–25 p.p.m.,based on the dry weight of the nodules, is needed for maximum nitrogen fixation in lucerne, and only 4–8 p.p.m. is adequate for subterranean clover. The addition of nitrate nitrogen to molybdenum-deficient plants improves growth. Where nodules do not function properly because of deficient molybdenum, the number of nodules on plant roots is likely to be greater than where molybdenum is adequate. This shows that ineffective nodules, whether due to ineffective bacterial strains or other reasons, tend to show a similar response. This is in line with the carbohydrate concept, discussed above; where adequate nitrogen is not present in the plant, carbohydrate accumulates and this in turn makes it possible for more nodules to form on the roots.

Boron also plays a role in symbiosis but apparently not as a catalyst like molybdenum. Boron is essential for the growth of meristematic tissues. It is also essential in building up normal nodules with a well-developed vascular system, and may thus indirectly have a favorable effect on nitrogen fixation.

Cobalt is a constituent of vitamin B_{12} and apparently this vitamin plays a part in the metabolism of the rhizobia. At least it is known that the element is required in trace amounts by plants that are dependent upon nodules for their nitrogen supply.

Iron is a constituent of hemoglobin that occurs not only in the red blood cells of vertebrates but also in effective nodules. In animals it acts primarily in the transport of oxygen from the lungs to the tissues of the body. Its exact role in legume nodules is not known but the hemoglobin seems to play a part, either direct or indirect, in the symbiotic fixation process.

Combined nitrogen

The amount of combined nitrogen in soil affects the number and size of nodules, and also the amount of nitrogen fixed. In a medium such as sand where fixed nitrogen is present only in traces, it has often been observed that the addition of a few p.p.m. of nitrogen will favor nodule formation. This is not surprising, for an appreciable amount of nitrogen is necessary for a seedling to start growth and build up nodular tissue; without nodules there can obviously be no fixation.

High levels of combined nitrogen can sometimes prevent all nodule formation; however, more often root infection occurs, but the nodules remain small and nitrogen fixation is greatly curtailed or entirely prevented. The main reason for such reduced nodulation is the lowered carbohydrate level as outlined above. Nitrogen fixation, except at very low levels of fixed nitrogen, tends to be inversely related to the amount of combined nitrogen added. Not all forms of fixed nitrogen produce the same effect and, likewise, the response of different legume species varies.

Many experiments conducted in the field or greenhouse show that crop yields are higher if legumes are grown on fixed nitrogen than if grown with air nitrogen as the only source of this element. In most experiments of this type we have no proof that the nodules were produced wholly by highly effective bacterial strains. More critical experiments to test this point are needed, but it is not illogical to suppose that fixed nitrogen will increase the production of dry matter. With abundant fixed nitrogen the plant is more succulent and is likely to have a more rapid early growth rate. A fast start almost invariably results in more total growth with any kind of plant. It is unlikely that any appreciable amount of the plant's carbohydrate supply is utilized as an energy source in the fixation process, which if it occurred would reduce fixation.

The effect of combined nitrogen on nitrogen fixation is therefore to suppress it, and often markedly except at very low levels. The statement is sometimes made that legumes prefer combined nitrogen over free nitrogen. Actually, they probably use the two nitrogen sources more or less interchangeably, and simultaneously. Any suppression of fixation by the added nitrogen would widen the ratio of combined nitrogen to nodular nitrogen and tend to increase the uptake of the former, and thus give the impression of its preferential use.

Associative action

When legumes and nonlegumes are grown in mixture the observation has been made frequently that the total dry weight and nitrogen content of crop produced on a unit area is often greater than when either crop is grown separately. The nonlegume in the mixture is likely to show a higher percentage of nitrogen when grown in such mixtures. Most experiments designed to determine if legumes excrete nitrogen that is assimilated by nonlegumes growing in close association have shown that such excretion occurs only in trace amounts. A few investigators have, however, shown that under certain environmental conditions considerable nitrogen can be excreted from legumes. Virtanen in Finland, for example, reported that 10–50% of the nitrogen fixed by peas grown in the greenhouse was excreted in the form of amino acids.

Much work done in various countries and with several legumes has shown that nitrogen is excreted only under rather abnormal environmental conditions. Apparently the deciding factor is that the rate of photosynthesis be so low that insufficient carbohydrate is formed to combine with all of the nitrogen as it is fixed. Any excess nitrogen may then occasionally, but only occasionally, be released from the roots of some legumes. This is such a difficult phenomenon to demonstrate that one must assume that a number of environmental conditions are exerting their effects simultaneously.

Mixed cropping of legumes and nonlegumes has often been shown to be a good practical cropping practice, particularly in pastures where the roots of the two types of plants are intertwined. If grasses and clovers, for example, are grown in association, the grass will usually assimilate almost all of the available nitrogen that is present, and the clover will obtain nearly all of its needs from the air. The result is likely to be that more nitrogen is fixed per acre even though the growth of the legume is partly inhibited as a result of grass competition. Such a beneficial result may be realized even if there is no excretion of nitrogen, but might be even more in evidence if there is some excretion.

Another important factor in mixed cropping is the transfer of nitrogen from legume nodules and roots as a result of the loss of nodules during unfavorable weather conditions or at other times of slow growth. This dropping of nodules is not as infrequent an occurrence as is generally supposed. These nodules are considerably higher in protein than are root tissues and hence decompose rapidly, thereby releasing the nitrogen for assimilation by any nonlegumes present. Furthermore, there is also a considerable continuous sloughing off of root hairs and other root tissues during normal growth. Most of the nitrogen released through these processes, as well as that constantly being released from soil organic matter throughout the growing season, finds its way into any nonlegumes growing in association.

The quantity of nitrogen fixed by legumes, growing in mixture with grasses, can be unexpectedly high. Values as high as 150–300 lb. per acre per year have been obtained fairly often in Australia and New Zealand, and there is at least one report of a 600-lb. increase (Walker et al., 1954; Walker, 1956). Since single crops of most legumes commonly fix only 100–200 lb. of nitrogen or less per acre, it would seem that the continuous removal of the available nitrogen in the soil by grasses does cause the legume to make full use of its nitrogen-fixing ability. This is somewhat surprising in view of the necessity for the legume to compete with grasses for nutrients, space and light. Furthermore, if the pasture is grazed, the constant removal of a portion of the tops would also reduce carbohydrate formation. This constant pruning action would stimulate new vegetative growth, which may perhaps stimulate fixation. Legumes show their maximum fixation when young, and constant grazing, if not too severe, may serve to extend the time for rapid fixation. Certainly, very close grazing would greatly decrease the amount of nitrogen fixed.

SYMBIOTIC FIXATION OF NITROGEN BY NONLEGUMES

Several genera of plants other than legumes have been shown to be able to fix elemental nitrogen when their roots bear nodules produced by a symbiotic endophyte. It is now generally held that the nodules are produced by actinomycetes but conclusive proof of this is still lacking. Bond (1967) gives a summary of our knowledge of this unique symbiotic relationship. Table 10.1, taken from his article, shows that 110 species out of a total of 310 in 13 genera have been reported to bear nodules. It will be noted that many of these genera are native to various parts of the world. All of these plants are dicotyledenous and woody. Further research will doubtless show that additional nonlegumes are also nodulated and capable of utilizing atmospheric nitrogen.

Attempts to isolate the nodule-producing organisms have met with little success, suggesting that in some cases the organism may be obligately symbiotic. Isolates of organisms from nodules have in most instances failed to infect test plants, thus throwing doubt on the claim that the causative organism was isolated. The difficulties involved here correspond closely with those experienced in work with mycorrhizal fungi.

The ability of various nodulated nonlegumes to utilize molecular nitrogen was usually

TABLE 10.1

SOME DETAILS OF THE NODULE-BEARING GENERA (from BOND, 1967)

Genus	*Number of species in genus*[1]	*Present distribution*	*Number of species recorded to bear nodules*
Coriaria	15	Mediterranean to Japan, New Zealand, Chile to Mexico	12
Alnus	35	Europe, Siberia, North America, Japan, Andes	25
Myrica[2]	35	many tropical, subtropical, and temperate regions	11
Casuarina	45	Australia, tropical Asia, Pacific Islands	14
Elaeagnus	45	Asia, Europe, North America	9
Hippophaë	1	Asia, Europe, from Himalayas to Arctic Circle	1
Shepherdia	3	North America	2
Ceanothus	55	North America	30
Discaria	10	Andes, Brazil, New Zealand, Australia	1
Dryas	4	Arctic and mountains of north temperate zone	1
Purshia	2	North America	2
Cercocarpus	20	North America	1
Arctostaphylos	40	Northwest and Central America, Europe, Asia	1

[1] Estimates prepared by Mr. H.K. Airy Shaw, Royal Botanic Gardens, Kew, for the new edition of Willis's *Dictionary of Flowering Plants and Ferns.*

[2] Including *Comptonia.*

first demonstrated by culturing plants with and without nodules in nitrogen-deficient media. Bond states that in such studies with the first eight genera shown in Table 10.I, the results have in all cases "been unequivocal and often dramatic – the nodulated plant grows well, even luxuriantly, and in a rapidly growing species such as *Alnus glutinosa* as much as 300 mg nitrogen per plant can accumulate, obviously by fixation, in the first season of growth from seed. In contrast, nodule-free plants, after exhaustion of the seed nitrogen, make little further growth."

In recent years the nitrogen-fixing ability of several of the genera has been demonstrated by a number of workers using the ^{15}N-tracer technique. Practically all of these studies have been conducted with plants grown under nonaseptic conditions, but the results are nevertheless conclusive and impressive. The fixation undoubtedly occurs in the nodule as is true of legumes. In fact, many of the nodules contain a "bacteroid type" of tissue and presumably fixation occurs in or near this tissue. Molybdenum and cobalt are required, as in legume nodules, and the fixation process is probably also reductive. Hemoglobin has been observed in some nodules, but usually in such small amounts as to throw doubt on its presence, and significance if present.

The nodulated nonlegumes, being shrubs and trees, are found for the most part in forests, waste places, bogs, and on sand dunes. They act as important pioneers in building up soil nitrogen. Non-nodulated tree species, growing in close association benefit from this fixed nitrogen although probably not by direct transfer. Cultivated crops utilize the stored-up nitrogen after the tree vegetation is removed.

Some evidence has been presented that certain plants infected with mycorrhizal fungi can fix small amounts of nitrogen, but conclusive proof of such claims must await further experimentation.

Root nodules are also found on the Cycadaceae that grow in tropical regions. In the nodule clusters, nitrogen-fixing blue-green algae are commonly present and they presumably are the agents of fixation although not the cause of nodulation. According to Bond, extensive fixation can occur in these cycad nodules, and the host plant benefits therefrom.

A few plant genera have been reported to form leaf nodules that some workers have shown to fix nitrogen. The causative agents are anaerobic or facultative anaerobic bacteria. The limited amount of information available on these leaf organisms is summarized by Bond.

MECHANISM OF NITROGEN FIXATION

The mechanism of nitrogen fixation is generally considered to be similar in both nonsymbiotic and symbiotic systems although most of the biochemical research has been with the former. The fixation process is undoubtedly a reductive process with little or no energy requirements, but the exact mechanism remains to be determined. Ammonia is considered a key compound in nitrogen fixation although not necessarily the first product of fixation. It does, however, stop fixation when it is added to a culture of actively-fixing bacteria. Molybdenum is essential as an activator of nitrogen fixation in both legumes and nonlegumes but vanadium serves as an inferior substitute in some of the free-living organisms. Iron is required for the formation of hemoglobin in legume nodules, and traces of cobalt seem to be essential for some of the bacteria.

In this book that deals with soil organic matter there is little need to discuss what is known about the biochemistry of the fixation process, or the various interesting theories that have been advanced. The reader who is interested in these matters should refer to the following articles: Wilson (1958), Mortenson (1962), Mortenson et al. (1962), Jensen (1965), as well as to numerous other references that are mentioned by these investigators. In recent years success has been achieved in the preparation of cell-free extracts of many of the nitrogen-fixing organisms and this should lead to rapid advances in the determination of the biochemical steps in the fixation process.

BIOLOGICALLY-FIXED NITROGEN VS FERTILIZER NITROGEN

Crop rotations with one or two years of legume crops every three to five years were until recently the standard recommendation to farmers engaged in general farming. Such a system helps to control plant diseases and insects, but the main purpose was to provide nitrogen via the legume for the nonlegume crops in the rotation. This legume nitrogen plus that released from the soil was adequate for fair-sized crop yields except on the poorer soils.

As commercial nitrogen became abundant at prices below the cost of growing legumes as a major crop, discussion raged as to the necessity both for rotations and for inclusion of a legume in the rotation. As is brought out in a later chapter, a careful evaluation of all of the information has led to the conclusion that it is usually most profitable and satisfactory to buy the nitrogen in the bag rather than to grow it. Purchased nitrogen can be applied at any rate and time desired, and the crop yields are likely to be higher than when the legume is the sole source of nitrogen.

Factors other than nitrogen must also be considered. If a legume crop is much needed for feed then it should be grown, since it has value other than as a nitrogen source. Likewise, a certain rotation with or without a legume may be valuable in certain soils for the purpose of improving soil aggregation and structure. Where diseases, insects or weeds are severe pests then here, again, a rotation may be advisable unless these can be more easily controlled by means of fungicides, insecticides, or herbicides. The need for organic matter maintenance may also emphasize the need for growing legumes either in the rotation or as catch crops. In pastures, seldom would commercial nitrogen be applied, since legumes can usually supply the needed nitrogen more cheaply and produce a more nutritious feed.

For a general discussion of the contributions of nitrogen-fixing green plants, including legumes, nonlegumes, and blue-green algae to our economy, reference should be made to the paper by Stewart (1967).

The availability in recent years of comparatively cheap nitrogen has, unfortunately, helped to bring into the foreground the matter of agricultural pollution. On some farms commercial nitrogen is being used in such large amounts that an unknown but possibly an appreciable portion of it escapes to the rivers and lakes either by direct runoff or more often as a result of leaching into the ground waters. In this position some of it may be lost to the air as gas; the remainder remains in the soil largely as nitrate. The underground waters may stay put or move on to streams, lakes, or oceans. The algal growths that appear in fresh waters, high in nitrogen, can be very harmful to fish as a result of decay and oxygen depletion. Lakes and streams may be made unsuitable for recreation purposes. There is need for more research data that will enable us to better evaluate the contribution of commercial nitrogen to the pollution problem. The logical solution is to apply nitrogen only in amounts and at times when the crop can utilize it promptly. This practice should almost completely eliminate nitrogen fertilizers as a source of pollution.

The availability of cheap nitrogen has also discouraged the hauling of animal manures and other wastes onto the cropland, and as a result the pollution caused by feedlots can also be highly objectionable. Practical methods for disposing of such wastes that are not applied to the soil are needed.

REFERENCES

Adams Jr., R.S. and Stevenson, F.J., 1964. *Soil Sci. Soc. Am., Proc.*, 28: 345–351.

Alexander, M., 1961. *Introduction to Soil Microbiology.* Wiley, New York, N.Y., 472 pp.

Allen, E.K. and Allen, O.N., 1959. *Recent Adv. Bot.*, 1: 585–588.

Allison, F.E., 1935. *Soil Sci.*, 39: 123–143.

Allison, F.E., 1947. *Soil Sci.*, 64: 413–429.

Allison, F.E., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 573–606.

Allison, F.E. and Morris, H.J., 1930. *Science*, 71: 221–223.

Allison, F.E., Hoover, S.R. and Morris, H.J., 1937. *Bot. Gaz.*, 98: 433–463.

Allison, F.E., Gaddy, V.L., Pinck, L.A. and Armiger, W.H., 1947. *Soil Sci.*, 64: 489–497.

Bond, G., 1967. *Ann. Rev. Plant Physiol.*, 18: 107–126.

Burton, J.C., 1959. *Recent Adv. Bot.*, 1: 596–600.

Cameron, R.E. and Fuller, W.H., 1960. *Soil Sci. Soc. Am., Proc.*, 24: 353–356.

Clark, F.E., 1948. *Soil Sci.*, 65: 193–202.

De, P.K. and Mandal, L.N., 1956. *Soil Sci.*, 81: 453–458.

Delwiche, C.C. and Wijler, J., 1956. *Plant Soil*, 7: 113–129.

Drewes, K., 1928. *Zentbl. Bakt., Abt. 2*, 76: 88–101.

Dugdale, R.C. and Neess, J.C., 1961. *Robert A. Taft Sanit. Eng. Cent., Tech. Rep.*, W61-3: 103–106.

Fred, E.B., Baldwin, I.L. and McCoy, E., 1932. *Univ. Wisc. Stud., Sci.*, 5. Univ. Wisc., Madison, Wisc., 343 pp.

Greenland, D.J., 1959. *Proc. Interafr. Soils Conf. 3rd*, : 531–535.

Greenwood, D.J., 1963. *Chem. Ind., London*, : 799–803.

Hanawalt, R.B., 1969a. *Soil Sci. Soc. Am., Proc.*, 33: 231–234.

Hanawalt, R.B., 1969b. *Soil Sci. Soc. Am., Proc.*, 33: 725–729.

Howard, D.L., Frea, J.I., Pfister, R.M. and Dugan, P.R., 1970. *Science*, 169: 61–62.

Jensen, H.L., 1940. *Proc. Linn. Soc. N. S. W.*, 65: 1–122.

Jensen, H.L., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 437–480.

Jensen, H.L. and Swaby, R.J., 1941. *Proc. Linn. Soc. N. S. W.*, 66: 89–106.
MacRae, I.C. and Castro, T.F., 1967. *Soil Sci.*, 103: 277–280.
Malo, B.A. and Purvis, E.R., 1964. *Soil Sci.*, 97: 242–247.
Meiklejohn, J., 1962. *Emp. J. Exper. Agric.*, 30: 115–126.
Moore, A.W., 1966. *Soils Fert.*, 29: 113–128.
Mortenson, L.E., 1962. In: I.C. Gunsalus and R.Y. Stanier (Editors), *The Bacteria.* Academic Press, New York, N.Y., pp. 119–166.
Mortenson, L.E., Mower, H.F. and Carnahan, J.E., 1962. *Bacteriol. Rev.*, 26: 42–50;
Nye, P.H. and Greenland, D.J., 1960. *The Soil Under Shifting Cultivation. Commonw. Bur. Soil Sci. G.B. Tech. Commun.* 51: 1–156.
Rovira, A.D., 1963. *Plant Soil*, 19: 304–314.
Ruinen, J., 1956. *Nature*, 177: 220–221.
Ruinen, J., 1961. *Plant Soil*, 15: 81–109.
Ruinen, J., 1965. *Plant Soil*, 22: 375–392.
Stevenson, F.J., 1959. *Science*, 130: 221–222.
Stewart, B.A., Viets Jr., F.G., Hutchinson, G.L., Kemper, W.D., Clark, F.E., Fairbourn, M.L. and Strauch, F., 1967. *U.S. Dep. Agric., A.R.S.*, 41-134: 1–206.
Stewart, W.D.P., 1967. *Science*, 158: 1426–1432.
Vasantharajan, V.N. and Bhat, J.V., 1968. *Plant Soil*, 28: 258–267.
Vincent, J.M., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 384–435.
Walker, T.W., Orchiston, H.D. and Adams, A.F.R., 1954. *J. Br. Grassl. Soc.*, 9: 249–274.
Walker, T.W., 1956. *J. Sci. Food Agric.*, 7: 66–72.
Wilson, P.W., 1958. *Ruhland's Handbuch der Pflanzenphysiologie.* Springer, Berlin, 8: 9–47.

Chapter 11

NONBIOLOGICAL IMMOBILIZATION OF NITROGEN

INTRODUCTION

When available nitrogen is added to soil as fertilizer, or is released from soil organic matter, rarely if ever is all of this available nitrogen recovered in the crop that follows. As stated elsewhere in this book, some of this nitrogen is usually biologically immobilized as fine rootlets that cannot be separated from the soil; as cells of microorganisms that live in the soil and on the plant roots; and as organic decomposition products and excretions derived from plant roots and microorganisms. Incomplete recovery of nitrogen, due to loss of nitrogen in gaseous forms, is discussed in Chapter 13.

Poor nitrogen recovery can also be the result of chemical or physical immobilization of the nitrogen. The importance of nonbiological immobilization of nitrogen has not been emphasized to any great extent until recent years, and even at present our knowledge of some phases of the subject is too meager to allow of definite quantitative appraisals of the practical importance of this type of nitrogen tie-up. The main methods by which available, water-soluble forms of nitrogen can be fixed nonbiologically in difficultly-available forms in soils are discussed here. These consist of: (1) reactions of ammonia with organic matter, chiefly lignin; (2) reaction of nitrite with lignin, or lignin-like materials; (3) fixation of ammonium in the clay lattices of certain minerals; and (4) fixation of ammonium as ammonium aluminum phosphates.

It should be added that certain organic compounds such as proteins, that contain nitrogen that is almost as available to plants as are ammonia and nitrate, may also be trapped in clay lattices and thereby become either nonavailable or very slowly available. This subject is discussed in Chapter 9.

In the present chapter the term fixation will be used frequently in referring to the four reactions mentioned above. It is difficult to give an exact definition for the term when applied to several mechanisms of fixation of nitrogen by several reactants as is done here. In general, the meaning is that the nitrogen so fixed is no longer soluble in water or readily extractable with a *N* KCl solution. In cases where organic matter is involved rather than clay minerals the reaction product may be resistant to hydrolysis with strong acids and alkalies. The term ammonium fixation has been defined officially (*Soil Sci. Soc. Am., Proc.*, 1965, 29: 331) as "the adsorption or absorption of ammonium ions by the mineral or organic fraction of the soil in a manner that they are relatively insoluble in water and relatively unexchangeable by the usual methods of cation exchange." This definition, so far as the end product is concerned, applies rather closely to the product of the four methods of fixation discussed here even though the reactants and the methods of fixation differ markedly.

Nonbiological immobilization of nitrogen is considered here even though organic matter is involved directly in only two of the four mechanisms mentioned above. Indirectly, organic matter plays an important part in all four of these mechanisms because nitrogen is in most respects the most important element in organic matter, and anything that affects it also affects the efficiency with which organic matter is utilized in crop production. The end product of organic matter decomposition is ammonia, and when this or its oxidation product, nitrite, is converted into water-insoluble and possibly unavailable nitrogen, one of the main benefits of soil organic matter may be lost or greatly reduced.

REACTION OF AMMONIA WITH ORGANIC MATTER

Nature and extent of the reaction

It has long been known that under some conditions ammonia can react with organic matter to form compounds that are not water soluble and not decomposed readily. The earlier literature on the subject is reviewed by Mortland (1958), and the later work by Nõmmik (1965) and Mortland and Wolcott (1965).

In the earlier work, dating back to about 1930, the interest was chiefly in developing a process for producing organic nitrogen fertilizers. One of the earlier workers mentioned by Mortland was able to raise the nitrogen content of peat to 15% by treating it with ammonia in the presence of oxygen and suitable catalysts. Feustel and Byers (1933) also found that peat, lignin, sulphite-waste liquor and soil organic matter reacted with ammonia. These reactions were carried out at temperatures from 50° to 225°C and for periods of 1 to 36 hours. The percent of added nitrogen taken up by peat ranged from 2.8 to 5.8.

Ammoniated peat prepared by Scholl and Davis (1933) contained up to 10.8% of nitrogen when the experiments were conducted at 180°C and up to 21.7% nitrogen when the temperature was 300°C. About three-fourths of the nitrogen was in a non-ammoniacal form and present as a water-insoluble complex of unknown composition. Using the same ammoniation system as described by Scholl and Davis, and a temperature of 180°C for 24 hours, Pinck et al. (1935) found that peat, lignin and starch yielded dark, brown, amorphous solids that contained 12.2, 9.1 and 5.4% nitrogen, respectively. Urea, apparently formed from CO_2 liberated during treatment, was present in these materials to the extent of 15.5, 18.1 and 4.5% of the total fixed nitrogen. The remaining organic nitrogen compounds consisted of a complex mixture of substances. The indications were that both the carbohydrate and lignin units of peat were extensively ammoniated. More recently, Mortland (1958) pointed out that it is known that ammonia can react with carboxyl, phenol, aldehyde, ketone, and alcohol groups to form amines, amides, and imides of various kinds. A variety of reactions of ammonia with lignin and soil organic matter therefore seem to be likely possibilities, at least under some conditions.

During the period of 1941 to 1955 Mattson and Koutler-Andersson were the most active contributors to our knowledge of ammonia–organic matter reactions. Their chief publications (six in number) are summarized in an excellent manner by both Mortland (1958) and Nõmmik (1965). They treated peat, lignin, humus, and various plant residues with aqueous solutions of ammonia and observed ammonia fixation proportional to the acidoid content. The product had a higher pH and isoelectric point than the original materials. Oxidation occurred simultaneously with ammonia fixation. Where oxidation occurred prior to fixation less ammonia was fixed, but the amount that could be fixed anaerobically was increased. The bond between the ammonia and the reactive group, possibly a carbonyl group, was shown to be quite stable since it was not broken by acid hydrolysis or chemical oxidation. About half of the combined ammonia was, however, removed by treatment with strong alkali.

In other studies by Mattson and Koutler-Andersson ammonia was shown to react with many substances of plant origin. They observed that ammonia produced by microbial activity was fixed by lignin during autoxidation, and that exchangeable ammonium was fixed by the organic complex. This occurs only at comparatively high pH values because it is ammonia and not the ammonium ion that reacts to form the organic complexes.

Bennett (1949) observed that the nitrogen content of commmercial lignin was increased substantially by treatment with concentrated ammonium hydroxide, but methylation essentially prevented fixation of the nitrogen. His work seems to support the conclusions of Mattson and Koutler-Andersson that simultaneous oxidation and ammonia fixation take place by way of the phenolic hydroxyl groups.

Mattson and Koutler-Andersson suggested that much or most of the nitrogen in soil humus originates from reaction with ammonia. They considered that in soils the oxidative ammonia fixation is related to the lignin fraction, and that aromatic rings and hydroxyl groups are involved.

Stevenson (1957) discussed this matter of lignin–ammonia complexes in soils and concluded that there is no proof that large quantities of soil nitrogen occur in this form. He considered that the evidence for the presence of such complexes is presumptive. Likewise, Bremner (1965) stated that "there is very little evidence to support the present assumption that the lignin or lignin-derived fraction of soil organic matter is primarily responsible for this fixation." He cites the work of others showing that in sugarcane bagasse the hemicellulose fraction, and not the lignin fraction, is largely responsible for ammonia fixation. He stated further that "the most obvious defect of the lignin–ammonia theory is that it does not account for the finding that more than 40% of the organic nitrogen in most surface soils is in the form of combined amino acids and amino sugars."

I also doubt that much of the nitrogen in soil humus is the result of ammonia–lignin reactions; if it is, then we must conclude that these reactions can proceed under conditions of extremely low concentrations of ammonia and in acid soils. At present there is no evidence for this. In fact, Mattson and Koutler-Andersson (1943), Broadbent et al. (1960), Nyborg (1969) and others stress the fact that this reaction is with ammonia and not with ammonium ion, and hence can occur only at the higher pH values. The concentrations of ammonia normally formed in soil biologically would not be high enough to raise the pH appreciably, and thus allow the reaction to proceed.

Sohn and Peech (1958) determined total ammonia fixation by a number of inorganic and organic soils from New York by treating the air-dry soils with anhydrous ammonia gas. The organic soils fixed considerably more ammonia than did the mineral soils. Acid soils containing large amounts of organic matter fixed the largest amounts of ammonia, and the fixation capacity was increased by heating. From the difference between the ammonia- and potassium-fixing capacities of the soils, and from the decrease in the extent of ammonia fixation following treatment with hydrogen peroxide, it was concluded that at least 50% of the fixation of ammonia could be attributed to the reaction of ammonia with soil organic matter.

Data obtained by Broadbent et al. (1960), shown here in part in Fig. 11.1, bring out very clearly the importance of soil reaction in ammonia fixation by soil organic matter. In these experiments the soils were wet with a solution containing 4% nitrogen as ammonium sulfate and allowed to stand for 4 hours at 10°C. Fixation occurred to only a limited extent below the neutral point but was almost a linear function of pH at higher values. Ammonia fixation proceeded in the absence of oxygen but in longtime experiments the fixation was more extensive in its presence. In the case of pure polyphenolic compounds, including orcinol, hydroquinone, and pyrogallol, ammonia was fixed only when oxygen

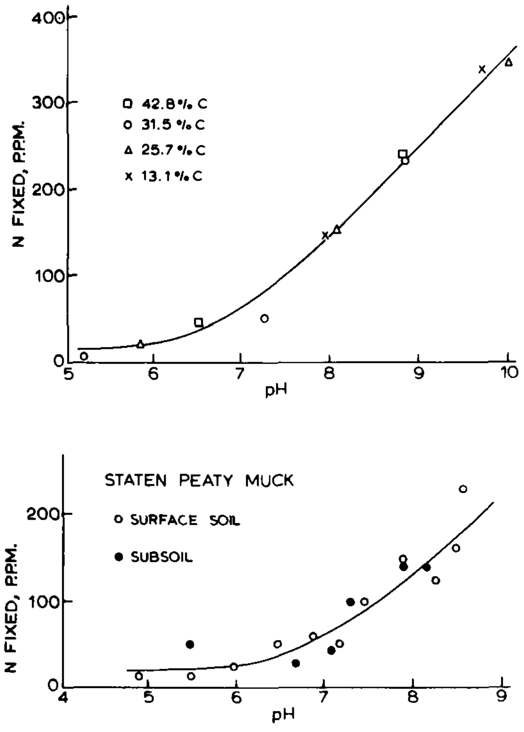

Fig. 11.1. Relation of ammonia fixation to pH in several soils. (From Broadbent et al., 1960.)

was present. These findings suggest that substances in the reduced state must undergo some oxidation in order to be subject to reaction with ammonia. They suggest further that reactive groupings capable of fixing ammonia are apparently in soils in sufficient amounts to permit the reaction to occur. When these active groups are saturated, oxygen would be needed for the formation of new active groups. These authors were of the opinion that the organic matter–nitrogen complex formed in soils in ammonia fixation may account in part for the resistance of soil organic nitrogen to biological attack.

The findings of Burge and Broadbent (1961) that ammonia fixation in organic soils of varying carbon content is linearly correlated with their carbon contents, and that the reaction occurs both in the presence and absence of oxygen, is of considerable significance (Fig.11.2). In the presence of oxygen, 1 molecule of ammonia was fixed per 29 atoms of carbon, and in its absence the value was 45 atoms of carbon. In these studies ammonia fixation could be attributed almost wholly to the organic fraction of the soil since removal of clay by treatment with a mixture of HCl and HF did not significantly affect the results. The authors considered that hydroxyl groups were involved in the fixation process but not aldehyde groups.

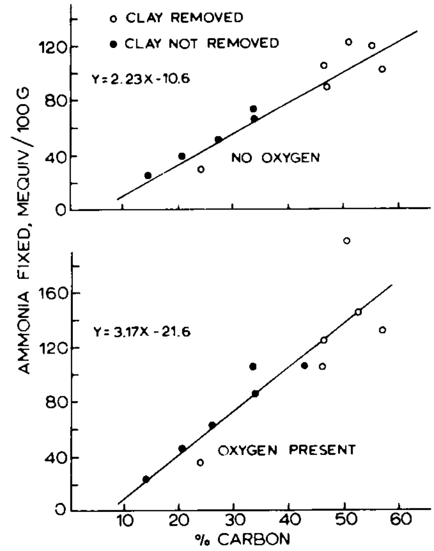

Fig. 11.2. Relationship between carbon content and ammonia fixation in several organic soils. (From Burge and Broadbent, 1961.)

Fixation studies conducted by Nyborg (1969) in both mineral and organic soils, using gaseous ammonia, showed that organic matter accounted for most of the fixation in the mineral as well as the organic soils. Fixation per 100 g organic matter averaged 87 mequiv. in the mineral soils. He observed "that fixation capacities were rather similar for the organic matter of divergent soils; that O_2 increased fixation by the same proportion in cultivated mineral soils and raw organic soils; that a substantial part of organically-fixed ammonia was labile; and that the organic matter in air-dry soils did not fix gaseous

NH_3 from light applications (less than 2 mequiv. per 100 g) that gave little increase in soil pH."

Jansson (1960) discussed the ability of lignin to fix ammonia and considered the possible mechanisms involved. He hypothesized that the ammonia nitrogen becomes bound to quinone configurations that are transitory in the autoxidation process. Quinone-imino groups are thus formed. By condensation and formation of heterocyclic rings the substances containing these groups become a part of the ligneous skeleton of soil organic matter. The resistance of lignin–ammonia complexes to chemical and biological attack would certainly indicate ring formation.

Mortland and Wolcott (1965) state that extensive studies dealing with model compounds indicate that the principal chemical reactions to be expected under natural conditions between ammonia and organic materials involve the oxygen-containing carboxyls, carbonyls, enolic, phenolic, or quinonic hydroxyl groups, or unsaturated carbon sites associated with these groups. In acid soils the concentration of reactive groups is low and likewise the capacity for ammonia fixation. The fixation that does occur is attributable to the slow production of oxidized groups. As the pH is raised and aeration is improved the structures become more polarized and reactive and the number of reactive groups is markedly increased, especially at pH values above 7. Fixation also increases with ammonia concentration and temperature.

From this incomplete summation of our knowledge of ammonia–organic matter reactions it is obvious that much ammonia can be fixed under conditions of increased temperature and pressures and with either high concentrations of aqueous ammonia or with anhydrous ammonia gas. The complex formed is so highly stable against both chemical and biological attack that it has not been deemed suitable for use as a fertilizer even though the product may contain up to 20% nitrogen.

It is probable that considerable ammonia may be tied up in complexes of unknown stability when much fertilizer nitrogen is added to organic soils or others rich in organic matter if the soil pH is high or is raised locally by the fertilizer. This means then that some of the nitrogen of anhydrous ammonia and ammonia solutions would almost certainly react with lignin or other constituents of the soil organic matter if unsaturated reactive organic groups were present. There is almost no likelihood that any appreciable amount of the ammonia being formed constantly by microorganisms in soil would react with lignin to form resistant complexes.

Biological availability of the immobilized nitrogen

Ammoniated peat prepared at temperatures of 180–300°C usually contains about a fourth of its total nitrogen in water-soluble form. About 40% of the water-soluble portion is in the form of urea and the remainder is in unknown forms. Nitrification tests (Davis et al., 1935) with these products showed that 13.4–31.0% of the total nitrogen was nitrified in soil during periods of 10–12 weeks. The water-soluble portion nitrified at about the same rate as ammonium sulfate, but only 6–17% of the insoluble residue was nitrified. Ammoniated lignin gave nitrification values similar to those for ammoniated peat. Ammoniated peat samples that according to the neutral permanganate method showed active nitrogen values of 80–90% gave nitrification values of only 10–11%.

In pot experiments conducted by Feustel and Byers (1933) the total nitrogen in ammoniated saw-grass peat was found to be 25–50% as available as that in inorganic nitrogen fertilizers. These treated peat samples contained only 2.8–5.8% of added nitrogen in contrast to the 10.6–18.5% contents of the samples studied by Davis et al. (1935). If we assume that availabilities obtained in vegetative tests are closely comparable with those obtained by nitrification (and they usually are), then it would seem that the more drastic the method used to fix ammonia in peat, and the more nitrogen so fixed, the lower the biological availability of the fixed ammonia.

In tracer experiments conducted by Burge and Broadbent (1961) a first crop of sudangrass took up 4.3% of the fixed nitrogen present in a muck subsoil, and the second cutting removed only 1.3%. This fixed nitrogen was derived from an ammonium sulfate solution that acted on the muck at pH 10 for 4 hours, followed by leaching with 0.1 *N* HCl. The amount of nitrogen so fixed was 350 p.p.m.

The three experiments mentioned above all show comparatively low availability to bacteria and higher plants of the ammonia fixed in the water-insoluble portions under conditions of high concentrations of ammonia, high pH, and sometimes high temperature. The conditions are entirely different in ordinary agricultural practice. Soils have been in equilibrium with ammonia for years and even centuries, and there would be little reason to expect much fixation to occur when very low concentrations of ammonia are formed in, or added to, soils, particularly at low pH values. It would be logical to expect that all or nearly all of such ammonia would remain in a sorbed and highly available condition.

In this connection it is pertinent to mention again that it has been estimated by several workers (see Chapter 10) that 20 to 40 lb. or more of ammonia nitrogen may be sorbed annually from the atmosphere by an acre of soil. In commenting on this, Mortland and Wolcott state that "if, as appears likely, the sorbed ammonia is quickly reverted to slowly available forms it would have little effect on current crop response." In the author's opinion there is only limited evidence at present that such quantities of ammonia enter the soil from the air except possibly around cities or industrial areas, and if it does, there is little likelihood that any appreciable portion of it would be fixed in the organic matter of arable soils. As stated above, appreciable fixation occurs only when both the ammonia concentration and pH are high.

There is still some uncertainty as to the availability of the nitrogen in any ammonia–organic matter complexes formed in soils as a result of the addition under field conditions of anhydrous ammonia or ammonia solutions. Since ammonia that is added in these forms gives crop responses that differ little from those produced by other nitrogen sources, it seems unlikely that complex formation is an important factor in the practical use of these nitrogen sources.

REACTION OF NITRITE WITH ORGANIC MATTER

Nature and extent of the reaction

Nitrite (or nitrous acid) is not only an unstable substance in acid soils but recent studies have shown that it is also quite reactive with certain constituents in soil organic matter, probably lignin or substances derived from lignin. Volatile forms of nitrogen (see Allison, 1965, 1966, and Chapter 13) are products both of the decomposition of nitrous acid and also of its reaction with soil organic matter. When it reacts with organic matter a portion of the nitrite–nitrogen is fixed by the organic matter and thus becomes a part of soil humus.

Bremner (1957) was probably the first to call attention to the reaction of nitrite with organic matter. In using the Van Slyke method to determine amino acids in humic acid preparations he obtained high results which he attributed to the reaction of nitrous acid with lignin or lignin-derived material. He states that the reaction of lignin with nitrous acid resembles the reaction of humic acid with nitrous acid in that it is accompanied by the fixation of nitrite nitrogen and the destruction of methoxyl groups. Prolonged hydrolysis with 6 *N* HCl removed only about a third of the fixed nitrogen, mostly in the form of ammonium but with a small amount of hydroxylamine.

The earlier conclusions of Bremner (1957), discussed above, have been largely confirmed by more recent tracer studies by Führ and Bremner (1964a,b), Bremner and Führ (1966) and Bremner and Nelson (1968). They found that the fixation of nitrite by soil organic matter occurs in both neutral and acid soils but much more rapidly under acid conditions. Air-drying favors the reaction. There was a distinct correlation between the amount of fixation and the amount of organic matter present. When 12.5 p.p.m. of nitrite–nitrogen was added to a soil of pH 5.1 that contained 2.2% organic carbon, one-fourth of the nitrite was fixed; when 500 p.p.m. nitrogen was added only 7% of it was fixed. During the time of the reaction 33–79% of the nitrite was released in gaseous forms. When the reaction product was boiled with 6 *N* HCl for 12 h, 50–60% of the nitrogen fixed by the soil organic matter was released, largely in the ammonium form. The evidence suggests that lignin-derived substances (phenols) are largely responsible for nitrite fixation, probably as aromatic nitroso compounds. Bremner and Nelson state that the phenolic substances "react readily with nitrite under soil conditions to form nitrosophenols that are decomposed by nitrous acid with formation of N_2 and N_2O."

Further proof of the reactivity of nitrous acid with organic matter has been supplied by the work of Stevenson and Swaby (1964). By means of manometric and infrared methods they showed that nitrous acid can react with lignin, humic acid, fulvic acid and polyphenols. The gases produced included nitrogen, nitrous oxide and methyl nitrite, formed when nitrous acid reacted with lignin and phenolic derivatives. The percentage of the nitrous acid that was fixed by these substances was not reported.

When 400 p.p.m. of nitrite–nitrogen was added to 4 soils, Reuss and Smith (1965) observed that about 40% of the nitrite was converted chemically to nitrogen gas in 24 h in a soil of pH 4.6; 12.0% and 9.5% in two soils of pH 5.6; and none in a soil of pH 7.8. Presumably, from the studies mentioned in the two preceding paragraphs, some of the nitrite reacted with the soil humus to form complexes but this was not determined. When a cation exchange resin was substituted for soil, no nitrogen gas was formed.

The ability of nitrous acid to react with common constituents of soil organic matter has also been demonstrated by Stevenson et al. (1970) in anaerobic experiments conducted in solutions buffered at pH 6–7 (see Chapter 13). These studies emphasize the kinds and amounts of gases produced rather than the amount of the nitrite that reacted with the organic compounds and was fixed by them; doubtless fixation considerably exceeded volatilization.

The experiments cited above are in general agreement with the conclusions of Clark and Beard (1960), Clark et al. (1960), and Broadbent and Clark (1965) that nitrite reactions with soil organic matter play an important role in the loss of nitrogen gas and nitrous oxide. Some of the results of Tyler and Broadbent (1960) can probably be explained in a like manner although the absolute proof is lacking. These workers did not determine how much, if any, of the nitrite was fixed by the organic matter.

Practical significance

The limited data now available seem to show beyond doubt that nitrite reacts readily with soil organic matter under ordinary conditions, especially in acid soils. The resistance of the complex to boiling in 6 *N* HCl, mentioned above, shows that the product is very stable. Bremner (1965) also states that the nitrogen in the complex is not readily mineralized by soil microorganisms. This means, then, that organic matter helps to fix nitrite–nitrogen in the humus and thereby prevents the escape of at least a portion of it to the atmosphere. This is important since nitrite is probably the most unstable nitrogen compound in soils.

The practical significance of this nitrite–organic matter reaction under field conditions is still largely unknown. Under most soil conditions nitrite is present only in traces. It is usually only when large amounts of ammonia fertilizers are added, or where a mass of green manure is turned under, that nitrite concentrations may reach comparatively high levels. Concentrations of 100 p.p.m. or more have been observed in soils near the point of application of anhydrous ammonia or liquid ammonia fertilizers. Under such conditions the nitrite accumulates for a short time because of the partial sterilization of the soil by the ammonia, and also because ammonia inhibits the nitrate-forming bacteria. Urea and Cyanamid may for the same reasons also result in nitrite accumulations. All of these fertilizers tend to raise the soil pH which, of course, reduces the rate of formation of the nitrite–organic matter complex. Nevertheless, according to Bremner, nitrite continues to react slowly. It is also important to emphasize that nitrite is stable at pH values near neutral and above, but decomposes rapidly at pH values below 5. This stability factor at high pH values where it can accumulate should more than compensate for its reduced rate of reaction at this pH level. In the light of this fact, it seems highly probable that the reaction may be of more practical importance than has been assumed. Of course if later work should show that the reaction rate at high soil pH values is much lower than presently published work indicates, then this would not be true.

It was pointed out above that nitrite is usually present only in traces in arable soils. We have always explained this by saying that nitrate-forming bacteria remove it as fast as formed. In the light of the newer knowledge we may need to emphasize that there is both a biological and a chemical demand for each bit of nitrite as the *Nitrosomonas* bacteria produce it.

The significance of the nitrite–soil organic matter reaction in connection with the loss of gaseous nitrogen in the forms of N_2 and N_2O is considered in Chapter 13.

FIXATION OF AMMONIUM BY CLAY MINERALS

The fate of ammonia in soils is a matter of great practical and scientific interest both because of the large amounts of nitrogen being applied in this form as fertilizer, and also because almost all nitrogen other than nitrate that finds its way into soils must pass through the ammonia stage on its way to assimilation by crops. Ammonia is sorbed very readily by both clays and soil organic matter, and the sorption can be either physical or chemical with all possible gradations between the two. Physically sorbed ammonia is readily removed from the adsorbent and hence remains readily available for plant use. The fact that ammonia is so readily sorbed and held against leaching is very fortunate, and constitutes one advantage that this material has over nitrates when it is used as a fertilizer. The present discussion is not concerned with this readily exchangeable ammonium but with the ammonium that is fixed in clays in a difficultly-exchangeable form.

Difficultly-exchangeable ammonium in clays is generally considered to be fixed by chemical reaction but, as stated above, there is no sharp line of demarcation between physical and chemical sorption. There is also no clear distinction between readily available and essentially nonavailable ammonia. Obviously, if fixation results in a marked decrease in availability to crops its efficiency in nutrition would be low. However, at intermediate degrees of sorption increased efficiency might be realized if sorption occurs at a time of excess concentration followed by a slow release later when the crop needs it.

In the discussion that follows some of the more important facts pertaining to mechanism of fixation by clays, and factors that affect fixation and release of the ammonium, will be considered. Our knowledge of several aspects of the subject is still incomplete but there is rather general agreement among soil scientists on the main phases of the subject.

Mechanisms of ammonium fixation

Fixation of difficultly-exchangeable ammonium by clay minerals is limited to the 2:1 type minerals. For information on the structure of clay minerals reference should be made to Hendricks (1945); Ross and Hendricks (1945); Gieseking (1949); Grim (1953);

and Rich and Thomas (1960). These include the vermiculites, illites (hydrous micas), montmorillonites, and interstratified minerals in which layers of two or more of the above types occur at random within a given particle. These minerals contain mica units, each of which consists of an octahedral sheet (Al^{3+} surrounded by 6 O^{2-} or OH^- ions) between two tetrahedral sheets (Si^{4+} surrounded by 4 O^{2-} ions). Usually a portion of the Al^{3+} ions is replaced by Mg^{2+} or Fe^{2+}, and a part of the Si^{4+} by Al^{3+} or other ions. This substitution leaves the lattice with a negative charge since the substituted ions have a lower valence than the Al^{3+} and Si^{4+} that they replaced. This charge is commonly neutralized by cations on the surface of the layers, mostly between the mica sheets. These cations may be either nonhydrated or associated with H_2O or OH^-. In unweathered micas, K ions usually predominate between the mica sheets but in the 2:1 clay minerals much of the K is commonly replaced by other ions, such as Na^+, Ca^{2+}, Mg^{2+} and H^+. These substituted ions are at least partially exchangeable, depending on whether the interlayer distance is sufficiently great for the ions to pass between the layers.

The 2:1 type clay minerals show marked variations in their degree of expansion. Montmorillonite has great expansibility of the lattice and high exchange capacity; vermiculite may expand as much as from 10 Å to 14 Å and commonly has an exchange capacity somewhat greater than montmorillonite; the hydrous micas show little or no expansion and lower exchange capacities than the other two clay minerals. The expanding clay minerals contract when air-dried.

Fixation of NH_4^+ and K^+ by vermiculite, degraded illite, and montmorillonite (Allison et al., 1953b; Barshad, 1951, 1954a,b; Allison and Roller, 1955b) occurs as a result of a trapping of these ions between the silica sheets. After these ions enter they come into contact with the negative electrical charges within the crystal. The contraction that occurs holds them so tenaciously that they are no longer readily exchangeable. Ions with considerably smaller diameters may enter the crystal lattice also but are held with less force and can be replaced by other ions. The size of the ions and the lattice opening, and the ease of expansion and contraction of the crystal lattice, are the chief determining factors in each individual case. Since montmorillonite contracts only when dried, it has no fixing power when kept moist. K^+ and NH_4^+ are ions of nearly the same size and behave similarly; when either is added in appreciable amounts, the other is prevented from entering the lattice. The addition of either reduces the total readily exchangeable ion content of the clay. Although this brief explanation of the mechanism of ammonium fixation gives the major facts as generally accepted today it is admittedly over-simplified. There are certain facts observed occasionally that appear to suggest that some modification of present views may be necessary as more information is obtained. For more detailed discussion of the subject reference should be made to articles by Nõmmik (1965) and Reitemeier (1951). Nõmmik presents a schematic picture showing the different forms of NH_4^+ as held by illite.

Page et al. (1967), working with vermiculitic soils, observed that in the wet state, fixation of NH_4^+ and K^+ can be attributed almost exclusively to ion-exchange. Under dehydrated conditions, if the amount of NH_4^+ and K^+ added does not exceed the capacity of the soil to fix these ions by the ion-exchange process, then fixation will likewise approximate cation-exchange capacity (CEC) reduction. However, with larger additions of NH_4^+ and K^+, the amount fixed upon dehydration will exceed the CEC reduction. In the latter case an additional fixation process seems to be involved.

Measurement of fixed ammonium

The term fixed ammonium, as applied to clay minerals, is commonly defined as the ammonium not removed by extraction with a *N* KCl solution. If K, Rb or Cs salts are added to a clay mineral the crystal lattice is contracted and any ammonium present in the lattice is held very tightly. Any ammonium not so held is readily leached out by the KCl solution. The separation between fixed ammonium on the one hand, and exchangeable and free ammonium on the other hand, is in this case very sharp and rapid. Salts of other elements, such as Na, Ca, Mg and Ba, or the acid HCl, cannot be used as extractants because they expand the lattice and there is no sharp endpoint; these substances may continue slowly to remove ammonium from the clays for a period of days or weeks. Defining fixed ammonium in terms of an extractant is obviously not entirely satisfactory, but it at least has the advantage of simplicity and a high degree of accuracy.

In studies with fixed ammonium we may wish to determine either: (1) the amount of fixation that occurs when dealing with dilute solutions; (2) the maximum fixation capacity; or (3) the amounts of fixed ammonium naturally occurring in soils.

In working with dilute solutions of ammonium it is common to add the ammonium to the soil quantitatively, allow it to react as long as desired, and then extract with *N* KCl. The amount not extracted is fixed ammonium. This may be determined by analysis of the solutions only. Accuracy is greatly increased if tagged ammonium is used.

In determining fixation capacity the soil is treated with a strong solution of ammonium salt and after a suitable time it is extracted with *N* KCl. The treated soil and the control can then be analyzed for total nitrogen and the fixation determined by difference. The accuracy is low with soils that are high in nitrogen and low in fixing capacity. Again, the ^{15}N-technique markedly increases accuracy.

Another method (Barshad, 1951) that has been used is to distill separate samples of an ammonium-treated soil with NaOH and with KOH. This method is based on the assumption that NaOH will remove both the exchangeable and the fixed ammonium, whereas KOH will remove the exchangeable ammonium only. Although this method has given good results under some conditions (see Hanway and Scott, 1956; Hanway et al., 1957; Leggett and Moodie, 1962, 1963), Allison and Roller (1955a) have shown that it is unsatisfactory for the determination of fixed NH_4^+ at levels below fixation capacity if appreciable quantities of readily exchangeable NH_4^+ are present in the soils being distilled. It is also unsatisfactory for use on soils that have been extracted with the chlorides of K, Ca, Mg, Na, and H, or where the soil organic matter fixes ammonium during the distillation. Furthermore, if any fixed ammonium is present, it will also be removed by the boiling NaOH. When used on unweathered minerals (Allison and Roller, 1955b) the method was less satisfactory than extraction with N KCl.

One of the best methods of determining fixed ammonium is by the use of a mixture of hydrofluoric acid and mineral acid to disintegrate the clay minerals and thereby release the fixed ammonium (Silva and Bremner, 1966). Unfortunately, the HF also extracts considerable organic matter (Stevenson et al., 1967), making it difficult to know just how much fixed ammonium is present. Methods of avoiding this need not be considered here. The method has the disadvantage of being rather laborious and time-consuming but is well suited to the determination of native fixed ammonium in soils and rocks. These methods are discussed by Nõmmik (1965)

Factors that affect the fixation process

Aside from the kind of clay mineral in the soil, already discussed, there are many factors that affect the rate and extent of fixation. Most of these are understood in a general way but some of the needed facts are lacking, and investigators differ on certain details, especially where mechanisms are involved. The more important information is summarized briefly below.

Degree to which the exchange sites are occupied

The amount of NH_4^+ that can be fixed by a clay mineral of the 2:1 type is dependent on the extent to which the exchangeable sites between the mica layers are already occupied by ions or substances that cannot be displaced readily. Pure mica, or unweathered illite, for example, has negligible NH_4^+-fixing capacity because the sites are occupied by K^+. As the mineral loses much of its potassium over the years, and the active spots are occupied by readily exchangeable Ca^{2+}, H^+, Na^+, etc., then the mineral can fix considerable NH_4^+.

Various organic substances, such as proteins, amino acids, antibiotics, etc. can enter some lattices and become complexed with the clay mineral. This occurs to the greatest extent with montmorillonite where the layer can expand readily to accommodate almost any size of molecule. The presence of such organic substances may prevent the entrance of NH_4^+ and therefore prevent its fixation. These large molecules may also keep the lattice expanded even though heated and dried, and if any NH_4^+ does enter, it is free to leave; in other words it remains in readily exchangeable form.

This competition for sites between the silica sheets explains in large part why surface soils commonly have a much lower capacity for fixing NH_4^+ than do subsoils, even though the entire soil profile contains the same kind of mineral. The surface soil usually contains a much larger amount of organic matter than does the subsoil and it has been shown many times that a considerable portion of this is bound to the clay. Furthermore, the surface soil is in equilibrium with the soluble ammonium and potassium ions that are always present; this means that the fixation capacity of the soil is already satisfied in part by the two ions that are capable of being fixed.

Amount and kind of ammonium added and rate of reaction

In a 2:1 clay mineral, or in a soil containing this type of mineral, it is generally believed that there exists an equilibrium between the three forms of ammonium present, as follows:

$$\underset{\text{soluble}}{NH_4^+} \rightleftharpoons \underset{\text{exchangeable}}{NH_4^+} \rightleftharpoons \underset{\text{fixed}}{NH_4^+}$$

Any increase in soluble or exchangeable ammonium will therefore increase the amount that is fixed. If a true equilibrium exists there should be a release of fixed ammonium when there is a reduction in the other two forms of ammonium. This reverse reaction seems to occur in some clay minerals very readily but in others it proceeds at such a slow rate as to leave considerable doubt as to whether difficultly-exchangeable ammonium is really in equilibrium with readily exchangeable ammonium. Ammonium is fixed in some clays so tenaciously that it seems to be prevented from reaction. More data are needed to clarify this situation. If an equilibrium, such as that mentioned above, does exist it would not involve NH_4^+ alone if K^+ were also present (Nõmmik, 1965) since these two ions are competitive.

An increase in the concentration of ammonium up to a certain maximum, increases the amount fixed (Allison et al., 1951). At low levels the percent fixed is comparatively high and decreases as more is added. Most of the fixation occurs during the first one or two hours but the maximum may not be attained for several hours. The rate of fixation increases with temperature, as would be expected.

Young and Cattani (1962) reported that fixation of anhydrous ammonia by the mineral fraction of several air-dry samples of soils from the Pacific Northwest exceeded by several-fold the wet fixation of nitrogen from aqua ammonia. In other studies, using degassed soils, Young (1964) observed that the major part of the ammonium not leachable with KCl was "associated with the organic fraction except in most subsurface horizons of the recent silty alluvial and water-deposited silt soils wherein the major part was fixed by the mineral fraction." In similar work with layer-silicate minerals, Young and McNeal (1964) observed wide variability in their retention of ammonia, and they stress the need for caution in applying data from a few specimen minerals to complex mixtures encountered in many soils.

Wetting and drying

The fixation of ammonium is usually increased by drying, especially when low concentrations are involved. In such cases drying increases the concentration of the ammonium solution and may also contract the clay lattice. In the case of montmorillonite, as already stated, no fixation occurs under moist conditions and hence drying is essential for any fixation to occur. Sometimes, but not always, alternate wetting and drying increases fixation. The effect observed is dependent primarily on whether the treatment increases the dehydration and contraction of the lattice.

Effect of grinding

In soils most of the ammonium-fixing capacity lies in the clay fraction (Schachtschabel, 1961; Nõmmik, 1965) but this may not be true of mineral specimens. McDonnell et al. (1959) observed that when vermiculite was subjected to ball milling a release of 90% of the fixed ammonium occurred after 230 h of dry grinding and after 435 h when kept wet during grinding. Dry milling of subsoils also resulted in the release of increasing amounts of ammonia with time.

The effect of grinding in hastening completion of the exchange reaction in vermiculite, according to Barshad (1954a), is "due to the increase in entry edge into the interior of the particle not only from a decrease in size but also from an increase in the number of fractures." Internal ammonium is thus made more accessible.

Interference by other cations

The cations that may be fixed by clay minerals include Rb^+ and Cs^+ in addition to NH_4^+ and K^+ (Joffe and Levine, 1947). Presumably they are all competitive although little work has been reported with Rb^+ and Cs^+. In the case of K^+ and NH_4^+ it is well established (Bower, 1950) that the addition of either to soil will reduce the fixation of the other added subsequently, and the reduction is nearly proportional to the amount added. This is also shown by the work of Stanford and Pierre (1947). Their work was with a soil in which montmorillonite was the predominant mineral but simular results have been obtained with vermiculite. The behavior of the ions differs somewhat with concentration, time of contact, and type of clay but these variables are usually of minor importance.

Using a K^+-fixing (and NH_4^+-fixing) soil to which a nitrification inhibitor had been added, Bartlett and Simpson (1967) observed that when K^+ was first added, later additions of NH_4^+ had almost no effect on the availability of the K^+; where NH_4^+ was added first and K^+ later, the availability of the K^+ was increased; and where the two ions were added simultaneously the availability of the K^+ was at least as high as where NH_4^+ was added before K^+.

Cations that are not fixed in clay lattices also tend to compete for active sites and thereby depress ammonium fixation. Nõmmik (1965) states that the depressive effect is as follows: $Na^+ < Mg^{2+} < Ca^{2+} < Ba^{2+} < H^+$.

Native fixed ammonium in soils, rocks and minerals

In the early studies of ammonium fixation there was much uncertainty as to the amount of fixed ammonium present in untreated soils. The capacity of the soil for fixing ammonium could be determined readily by the methods already mentioned, but such techniques furnished no information on the amount of fixed ammonium present initially. Since surface soils usually fixed less ammonium than did subsoils, it seemed likely that this was because the surface soils already contained fixed ammonium, and also potassium. Determination of naturally-occurring fixed ammonium was difficult because it was not known if the Kjeldahl method for total nitrogen actually accounted for all of the fixed ammonium. Furthermore, the organic nitrogen present also added to the analytical difficulties. Much progress toward the solution of this problem was made when Rodrigues (1954) introduced the idea of using a mixture of hydrofluoric and sulfuric acids to digest the minerals, thereby releasing any ammonium present in the clay lattices. This treatment was not entirely satisfactory because it also released some ammonia from the soil organic matter. Dhariwal and Stevenson (1958) largely overcame this difficulty by removing most of the organic matter by heating with KOH prior to the addition of the hydrofluoric acid. Other procedures for accomplishing the same thing have been suggested (Nõmmik, 1965) but will not be reviewed here. The method of Dhariwal and Stevenson is satisfactory and the KOH removes all but traces of the organic matter that would be decomposed by the HF treatment. These studies, together with the work of Stewart and Porter (1963), have shown very definitely that many surface soils do contain fixed ammonium and that the Kjeldahl method does not release all of the nitrogen that is trapped in clay lattices. Reference should be made to the paper by Bremner et al. (1967) for a comparison and evaluation of methods of determining fixed ammonium in soils.

Stevenson (1959a) analyzed a number of soils that are representative of several great soil groups and found that 3.5 to 7.9% of the nitrogen in the surface soils was in the form of fixed ammonium. With increasing depth of the soil profile the relative amount of nitrogen as fixed ammonium increased markedly. In one silt loam sample, taken at a depth of 68–82 inches, 81.7% of the nitrogen was fixed ammonium. This increase in percent with depth is attributable chiefly to the decrease in organic nitrogen with depth. Hinman (1964), likewise, found that in 5 profiles of soils of different textures the fixed ammonium content ranged from 7% of the total nitrogen in the surface soil to as much as 58% in the soil at a depth of 4 ft.

These findings of Stevenson (1959a) and Hinman (1964) are in agreement with the earlier results reported by Rodrigues (1954), and several other workers (Young and Cattani, 1962), in showing that the narrowing of the carbon–nitrogen ratio with soil depth is due primarily to the presence of considerable fixed ammonium in subsoils. When carbon–nitrogen ratios are based on organic nitrogen only, rather than on total nitrogen, the ratios decrease much less with depth of profile. Stevenson (1959a) has, however, shown that there is some narrowing of the ratios with depth even when fixed ammonium is excluded. This is also shown very well in Table 11.I, taken from the work of Moore and Ayeke (1965). Stevenson attributes this to the presence of a relatively higher amount of nitrogen-rich constituents in the organic matter of the subsoil in comparison with surface soil.

Fixed ammonium naturally present in soils varies of course with the type of clay mineral present. It also usually, but not always, increases with decrease in particle size, thus emphasizing the primary role of the clay fraction. Where this relationship to particle size does not hold one would suspect the presence of considerable vermiculite, since coarse particles of this mineral have high fixing powers.

Native fixed ammonium in several Hawaiian soils was found by Mikami and Kanehiro (1968) to a range from 0 to 585 p.p.m. Basaltic soils had a higher content of fixed

TABLE 11.I

TOTAL ORGANIC CARBON, KJELDAHL NITROGEN, HYDROFLUORIC-ACID-EXTRACTABLE AMMONIUM NITROGEN AND CARBON–NITROGEN RATIOS IN VARIOUS HORIZONS OF FOUR NIGERIAN SOIL PROFILES (from MOORE and AYEKE, 1965)

Depth (inches)	*Organic carbon (%)*	*Kjeldahl nitrogen (p.p.m.)*	*C:N*	*HF-extractable NH_4 N (p.p.m.)*	*HF-extractable NH_4 N / Kjeldahl N (%)*	*Organic C / organic N*
Ibadan profile						
0–4	0.92	504	18	32	6	19
4–11	0.47	369	13	43	12	14
11–39	0.27	329	8	109	33	12
39–61	0.14	244	6	133	55	13
61–86	0.08	238	3	149	63	9
Umuahia profile						
0–6	1.02	976	10	30	3	11
6–10	0.81	830	10	35	4	10
10–17	0.46	540	8	38	7	9
17–24	0.38	495	8	48	10	8
24–30	0.31	434	7	57	13	9
30–39	0.26	388	7	68	18	8
39–50	0.21	344	6	72	21	8
50–63	0.18	286	6	76	27	9
63–72	0.08	244	3	109	45	6
Benin profile						
0–3	1.86	1,450	13	32	2	13
3–6	0.56	583	10	38	7	10
6–9	0.26	315	8	43	14	10
9–12	0.32	396	8	68	17	10
12–18	0.28	398	7	83	21	9
18–24	0.17	262	6	84	32	9
24–36	0.14	237	6	84	35	9
36–48	0.12	215	6	86	40	9
48–60	0.09	174	5	88	51	10
276	0.04	231	2	147	64	5
Yo profile						
0–11	0.93	705	13	33	5	14
11–27	0.13	135	10	36	27	14
27–46	0.12	144	8	40	28	12
46–62	0.18	239	8	73	31	11
62–80	0.33	485	7	220	45	13
80–86	0.05	204	2	115	56	6

ammonium than did the volcanic ash soils. Likewise, the native fixed ammonium as a percent of total nitrogen was greater in the basaltic soils.

Rocks, as well as soils, contain nitrogen, a portion of which is present as fixed ammonium. Stevenson (1959b) found that six granite rocks contained an average of 40 p.p.m. of nitrogen, a fourth to a half of which was held as ammonium within the lattice of the silicate mineral; corresponding data for 4 shales were 650 p.p.m. of total nitrogen of which 60%, on the average, was fixed ammonium.

The origin of the fixed ammonium in rocks is not known with certainty but Stevenson expressed the opinion that "ammonium was present in the substrate at the time the minerals were synthesized and competed with potassium for the pockets formed by the hexagonal oxygen rings in the crystalline nuclei of the minerals." He states further that "if it is assumed that an average of one-third of the nitrogen in igneous rocks, and one-half of that in sediments, is fixed ammonium, the amount of nitrogen present as fixed ammonium in the earth's crust would be almost 20 times that present as elementary nitrogen in the atmosphere." Very likely the nitrogen in the atmosphere came originally from the earth, and the amount of gaseous nitrogen in the air has increased gradually during geologic times.

Additional data, reported by Adams and Stevenson (1964), are shown here in Table 11.II. The igneous rocks commonly contained up to 78 p.p.m. of ammonium nitrogen, 85% of which, on the average, was nonexchangeable. Most mineral samples contained

TABLE 11.II

TOTAL AMMONIUM AND NONEXCHANGEABLE AMMONIUM CONTENTS OF ROCK AND MINERAL SAMPLES (from ADAMS and STEVENSON,1964)

Sample	*Initial sample (p.p.m.)*		*NH_4-treated sample (p.p.m.)*	
	total	*nonexchangeable*	*total*	*nonexchangeable*
Rocks:				
Granite A	78	64	600	244
Granite B	28	25	103	51
Granite C	13	11	123	43
Granite D	32	26	273	110
Pegmatite A	21	20	101	35
Minerals (feldspar):				
Albite A	8	7	132	35
Albite B	4	4	102	36
Anorthite A	8	7	214	27
Microcline A	11	10	228	54
Microcline B	8	7	207	55
Orthoclase A	23	22	195	48
Orthoclase B	12	8	223	45
Minerals (mica):				
Biotite A	36	32	209	116
Biotite B	11	10	75	47
Muscovite A	11	10	258	108
Muscovite B	12	11	162	42
Minerals (miscellaneous):				
Beryl A	6	3	56	29
Beryl B	11	8	82	23
Quartz A	15	13	36	24
Quartz B	4	1	25	15

much less ammonium. When ammonium was added to the igneous rocks and primary silicate minerals, followed by extraction with *N* KCl, 15 to 244 p.p.m. of the nitrogen was retained as nonexchangeable ammonium. This was 3 to 15 times the amount of ammonium in the samples originally. The authors state that some ammonium was absorbed at the particle surface and some penetrated between the particles. They made the further observation that a portion of the nonexchangeable ammonium was released readily by treatment with hot *N* KOH. Ammonium fixation by igneous rocks was attributed primarily to micas.

Biological availability of fixed ammonium

Much effort has been exerted in recent years in an attempt to determine the availability of fixed ammonium to bacteria and higher plants. The results have often not been in close agreement but this is not unexpected since the variables encountered in studies of this type have been shown to be very numerous. Seldom have two workers conducted experiments with the same soils or minerals under the same conditions, even though attempts to do this may have been made. The detailed experimental work has been thoroughly reviewed by Nõmmik (1965) and hence only the main findings will be given here.

It was pointed out above that it is generally believed that fixed ammonium is in equilibrium with readily exchangeable ammonium, or with exchangeable ammonium plus potassium ions. There seems to be little doubt that such an equilibrium commonly exists in soils, but there is doubt as to whether it exists in certain unweathered 2:1 type minerals; also in some rocks any such equilibrium seems to be either nonexistent or the rates of change so slow as to be inconsequential. Fixed ammonium as we have defined it can under some conditions be as available as the ammonium in ammonium sulfate, or under other conditions essentially completely unavailable within the usual experimental period of a few days to six months.

Much of our knowledge of availability of fixed ammonium has been based on nitrification tests, since it is well established that any nitrogen that undergoes oxidation to nitrates in soil is available for use by higher plants. This represents the minimum that is available; it is likely that some plants can assimilate some of the nitrogen that *Nitrosomonas* cannot utilize, especially if the plants are removing ions or other substances that interfere with the release of ammonium from the clay lattices.

The availability of fixed ammonium in a large number of representative surface soils and subsoils of the United States was determined by Allison et al. (1953a). These data are typical of many other published results (Welch and Scott, 1960; Baert-DeBievre et al., 1961). In the experiments of Allison et al. the availability of fixed ammonium to nitrifying bacteria during a period of two months varied over the range of 5 to 24%, being lowest for vermiculite-containing soils and highest for those containing montmorillonite. Leaching with $CaCl_2$ as compared with KCl resulted in somewhat higher availabilities of the residual ammonium. This effect may be attributed to the fact that potassium contracts the crystal lattice and also blocks the release of any ammonium trapped inside. In the presence of calcium the lattice is expanded and hence the release of trapped ammonium is favored.

In studies with several subsoils selected because each contains a high percentage of a single clay mineral, the fixation capacities varied between 1.6 and 4.0 mequiv. per 100 g when air-dried and between 3.1 and 6.3 mequiv. when heated at 100°C (Allison et al., 1953c). Soils high in vermiculite have the highest values under moist and air-dry conditions, but when heated the illitic soils fixed the most ammonium. The Yolo silt loam subsoil, which is high in montmorillonite, had only about half the fixing power of two illitic soils. In these studies the availability of the fixed ammonium in all soils, as determined by nitrification, was in the range of 0 to 14.8% and averaged 5%. The lowest values were obtained with soils high in vermiculite and illite, and the highest with soils having chiefly montmorillonite. Potassium salts slightly depressed availability. The nitrification values increased only slightly when the incubation period was extended beyond 4 weeks.

Considerable caution is needed in making general statements about the behavior of ammonium-fixing minerals, both in soils and in geologic specimens. In soils, the degree of weathering (Jackson et al., 1952; Harada and Kutsuna, 1954, 1955) especially of illites, is important since such weathering usually markedly increases fixation, at least within limits. Furthermore, even different geological specimens of mineral vary in fixing power and in the ease of release of ammonium. The data of Allison et al. (1953b) illustrate this point. In studies with two samples of vermiculite minerals from the United States that had fixing capacities of 46 and 80 mequiv. per 100 g this fixed ammonium was nearly as available to nitrifying bacteria as was that in ammonium sulfate. After these studies were completed, these authors received a sample of vermiculite from South Africa and subjected this mineral to similar tests. It fixed 60 mequiv. of ammonium per 100 g. In nitrification studies lasting two months only 11% of the fixed ammonium was available where the samples had been leached with N KCl, and 16% where leached with N $CaCl_2$. These observations show that natural vermiculites vary with respect to both fixing capacities and ease of release of the ammonium.

The well-established fact that potassium interferes with the release of NH_4^+ from clay minerals, and the effect commonly increases with concentration, has led to the use of heterotrophic bacteria as agents for the determination of availability of fixed ammonium. These organisms have a much higher requirement for potassium than do the nitrifiers. Hence, experiments have been performed (Nõmmik, 1965) in which carbohydrates have been added to soils containing different amounts of fixed ammonium and the amount of CO_2 evolved determined. Such experiments have shown that this method of measuring the availability of fixed ammonium is fairly satisfactory provided the added energy source is readily available and free from potassium. Data on this method are still inadequate but present evidence indicates that the nitrification method is much to be preferred as a routine method.

Data on the availability of fixed ammonium to higher plants is rather confusing. Most of the work reported has been conducted in pot experiments where the mass of roots per unit of soil is considerably greater than in the field, which might favor slightly the uptake of ammonium. In addition, in pot experiments the tendency is to use higher rates of nitrogen than in the field.

In greenhouse experiments, availabilities of fixed ammonium as low as 7% have been reported (Bower, 1951; Allison et al., 1953c). Other experiments (Legg and Allison, 1959: Axley and Legg, 1960) have shown that nitrogen added in the form of ammonium was almost as available as if in the form of nitrate except where considerable potassium was present. In such comparisons it is common to observe that nitrate is assimilated much more rapidly than ammonium, suggesting that there is an equilibrium between fixed ammonium and readily exchangeable ammonium, but the movement in the direction of available ammonium involves an appreciable amount of time.

Under greenhouse conditions Peterburgsky and Smirnov (1966) observed that ammonium was used very poorly by plants. In these soils of the U.S.S.R. the chernozems fixed ammonium in considerably greater quantities than did podzolic soils. The ability to fix ammonium increased with decrease in soil particle size and also with profile depth.

The interference of potassium with ammonium release to plants has been observed in pot experiments by a number of workers (Walsh and Murdock, 1963). The facts here closely parallel the observations made in connection with nitrification. Obviously if high availability of the ammonium is desired it is not wise to add much potassium simultaneously with ammonium, but the potassium could be added sometime in advance of the ammonium.

One explanation for the apparent lack of agreement of the availability experiments is that all workers do not use the same test crop. Under greenhouse conditions it has been demonstrated that there is a marked difference in the ability of crops to assimilate fixed ammonium. Usually those investigators who have reported high availabilities have used cereal crops. Legg and Allison (1959) also obtained high values with sudangrass. In the low availability experiment of Allison et al. (1953c), the test crop was millet. Other crops that have given comparatively low values include mustard, sugar beets and potatoes. In a few experiments there has been clear-cut evidence that fixed ammonium not removed by a first crop is gradually removed by later crops. In some cases the residual effect can be large, but this of course varies with the experimental conditions and test crop.

There is essentially no quantitative data on the availability of fixed ammonium under field conditions. It seems safe to conclude, nevertheless, that the observations made in nitrification and pot experiments will hold fairly well under field conditions if comparisons are made between equal concentrations of added ammonium, and similar soil treatments are made. It is also necessary to bear in mind that most surface soils have a very low fixing capacity; high-fixing subsoils would have little effect on the availability of ammonium applied to the plowed layer.

In view of the various factors discussed above that affect the availability of fixed ammonium in soils, it is evident that the term "fixed ammonium" is a very general one; all such ammonium is not fixed to the same extent. For example, native fixed ammonium is fixed so tenaciously that it is practically unavailable (Keeney and Bremner, 1966), whereas ammonium recently added to soils is usually much less firmly fixed. As pointed out above, often much of this recently added ammonium is released to nitrifying organisms or to crops fairly readily.

There is some uncertainty as to whether ammonium fixation should be considered as a desirable or undesirable property of a field soil. If rapid availability of the nitrogen is important it is obvious that ammonium fixation is probably undesirable. If this is not especially important it is likely that the fixation process favors efficiency of use of the nitrogen both by prevention of losses by leaching and by making the nitrogen slowly available over a longer period of time. Eventually most of the nitrogen is recovered even if the first crop does not get all of it.

FIXATION OF AMMONIUM AS AMMONIUM ALUMINUM PHOSPHATE

Several recent investigators, cited by Nõmmik (1965), have shown that ammonium may be fixed in some Hawaiian amorphous soils in the form of slightly soluble crystalline substances, such as ammonium taranakite ($H_6(NH_4)_3Al_5(PO_4)_8 \cdot 18\ H_2O$). This substance can form where NH_4, Al, P, and moisture are present and the soil is acid. Clay minerals of the 2:1 type are not involved in the formation of this comparatively insoluble compound.

The practical significance of this possible reaction in ammonium availability and in crop production has not been determined, but it is not believed to be very great.

REFERENCES

Adams, R.S., and Stevenson, F.J., 1964. *Soil Sci. Soc. Am., Proc.*, 28: 345–351.
Allison, F.E., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 573–606.
Allison, F.E., 1966. *Adv. Agron.*, 18: 219–258.
Allison, F.E. and Roller, E.M., 1955a. *Soil Sci.*, 80: 349–362.
Allison, F.E. and Roller, E.M., 1955b. *Soil Sci.*, 80: 431–441.
Allison, F.E., Doetsch, J.H. and Roller, E.M., 1951. *Soil Sci.*, 72: 187–200.
Allison, F.E., Kefauver, M. and Roller, E.M., 1953a. *Soil Sci. Soc. Am., Proc.*, 17: 107–110.
Allison, F.E., Roller, E.M. and Doetsch, J.H., 1953b. *Soil Sci.*, 75: 173–180.
Allison, F.E., Doetsch, J.H. and Roller, E.M., 1953c. *Soil Sci.*, 75: 373–381.
Axley, J.H. and Legg, J.O., 1960. *Soil Sci.*, 90: 151–156.
Baert-De Bievre, M., Van den Hende, A. and Lox, F., 1961. *Pedologie*, 11: 104–118.
Barshad, I., 1951. *Soil Sci.*, 72: 361–371.
Barshad, I., 1954a. *Soil Sci.*, 77: 463–472.
Barshad, I., 1954b. *Soil Sci.*, 78: 57–76.
Bartlett, R.J. and Simpson, T.J., 1967. *Soil Sci. Soc. Am., Proc.*, 31: 219–222.
Bennett, E., 1949. *Soil Sci.*, 68: 399–400.
Bower, C.A., 1950. *Soil Sci.*, 70: 375–383.
Bower, C.A., 1951. *Soil Sci. Soc. Am., Proc.*, 15: 119–122.
Bremner, J.M., 1957. *J. Agric. Sci.*, 48: 352–360.

Bremner, J.M., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 93–149.

Bremner, J.M., Nelson, D.W. and Silva, J.A., 1967. *Soil Sci. Soc. Am., Proc.*, 31: 466–472.

Bremner, J.M. and Führ, F., 1966. *Use of Isotopes in Soil Organic Matter Studies. Rep. F.A.O.–I.A.E.A. Tech. Meet.* Pergamon, New York, N.Y., pp. 337–348.

Bremner, J.M. and Nelson, D.W., 1968. *Trans. Int. Congr. Soil Sci., 9th, Adelaide, S.A., II*: 495–503.

Broadbent, F.E., Burge, W.D. and Nakashima, T., 1960. *Trans. Int. Congr. Soil Sci., 7th, Madison, Wisc., Comm.*, III: 509–516.

Broadbent, F.E. and Clark, F.E., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 344–359.

Burge, W.D. and Broadbent, F.E., 1961. *Soil Sci. Soc. Am., Proc.*, 25: 199–204.

Clark, F.E., Beard, W.E. and Smith, D., 1960. *Soil Sci. Soc. Am., Proc.*, 24: 50–54.

Clark, F.E and Beard, W.E., 1960. *Trans. Int. Congr. Soil Sci., 7th, Madison, Wisc. Comm.*, III, 501–508.

Davis, R.O.E., Miller, R.R. and Scholl, W., 1935. *J. Am. Soc. Agron.*, 27: 729–737.

Dhariwal, A.P.S. and Stevenson, F.J., 1958. *Soil Sci.*, 86: 343–349.

Feustel, I.C. and Byers, H.G., 1933. *U.S. Dep. Agric., Tech. Bull.*, 389: 1–32.

Führ, F. and Bremner, J.M., 1964a. *Atompraxis*, 10: 109–113.

Führ, F. and Bremner, J.M., 1964b. *Landwirtsch. Forsch.*, 18: 43–51.

Gieseking, J.E., 1949. *Adv. Agron.*, 1: 159–204.

Grim, R.E., 1953. *Clay Mineralogy.* McGraw-Hill, New York, N.Y., 384 pp.

Hanway, J.J. and Scott, A.D., 1956. *Soil Sci.*, 82: 379–386.

Hanway, J.J., Scott, A.D. and Stanford G., 1957. *Soil Sci. Am., Proc.*, 21: 29–34.

Harada, T. and Kutsuna, K., 1954. *Bull. Nat. Inst. Agric. Sci., Ser. B*, 3: 17–41.

Harada, T. and Kutsuna, K., 1955. *Bull. Nat. Inst. Agric. Sci., Ser. B*, 5: 27–36.

Hendricks, S.B., 1945. *Ind. Eng. Chem.*, 37: 625–630.

Hinman, W.C., 1964. *Can. J. Soil Sci.*, 44: 151–157.

Jackson,M.L., Hseung, Y., Corey, R.B.,Evans, E.J. and Van den Heuvel, R.C., 1952. *Soil Sci. Soc. Am., Proc.*, 16: 3–6.

Jansson, S.L., 1960. *K. Lantbruks-Högskol. Ann.*, 26: 51–75.

Joffe, J.S. and Levine, A.K., 1947. *Soil Sci.*, 63: 151–158.

Keeney, D.R. and Bremner, J.M., 1966. *Soil Sci. Soc. Am., Proc.*, 30: 714–719.

Legg, J.O. and Allison, F.E., 1959. *Soil Sci. Soc. Am., Proc.*, 23: 131–134.

Leggett, G.E. and Moodie, C.D., 1962. *Soil Sci. Soc. Am., Proc.*, 26: 160–163.

Leggett, G.E. and Moodie, C.D., 1963. *Soil Sci. Soc. Am., Proc.*, 27: 645–648.

McDonnell, P.M., Stevenson, F.J. and Bremner, J.M., 1959. *Nature*, 183: 1414–1415.

Mattson, S. and Koutler-Andersson, E., 1943. *K. Lantbruks-Högskol. Ann.*, 11: 107–134.

Mikami, D.T. and Kanehiro, Y., 1968. *Soil Sci. Soc. Am., Proc.*, 32: 481–485.

Moore, A.W. and Ayeke, C.A., 1965. *Soil Sci.*, 99: 335–338.

Mortland, M.M., 1958. *Adv. Agron.*, 10: 325–348.

Mortland, M.M. and Wolcott, A.R., 1965. In: W.V. Bartholomew and F.W. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 150–197.

Nõmmik, H., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 198–258.

Nyborg, M., 1969. *Soil Sci.*, 107: 131–136.

Page, A.L., Burge, W.D., Ganje, T.J. and Garber, M.J., 1967. *Soil Sci. Soc. Am., Proc.*, 31: 337–341.

Peterburgsky, A.V. and Smirnov, P.M., 1966. *Plant Soil*, 25: 119–128.

Pinck, L.A., Howard, L.B. and Hilbert, G.E., 1935. *Ind. Eng. Chem.*, 27: 440–445.

Reitemeier, R.F., 1951. *Adv. Agron.*, 3: 113–164.

Reuss, J.O. and Smith, R.L., 1965. *Soil Sci. Soc. Am., Proc.*, 29: 267–270.

Rich, C.I. and Thomas, G.W., 1960. *Adv. Agron.*, 12: 1–39.

Rodrigues, G., 1954. *J. Soil Sci.*, 5: 264–274.

Ross, C.S. and Hendricks, S.B., 1945. *U.S. Geol. Surv., Prof. Pap.*, 205B: 23–79.

Schachtschabel, P., 1961. *Z. Pflanzenernähr. Düng. Bodenkd.*, 93: 125–136.

Scholl, W. and Davis, R.O.E., 1933. *Ind. Eng. Chem.*, 25: 1074–1078.
Silva, J.A. and Bremner, J.M., 1966. *Soil Sci. Soc. Am., Proc.*, 30: 587–594.
Sohn, J.B. and Peech, M., 1958. *Soil Sci.*, 85: 1–9.
Stanford, G. and Pierre, W.H., 1947. *Soil Sci. Soc. Am., Proc.*, 11: 155–160.
Stevenson, F.J., 1957. *Soil Sci. Soc. Am., Proc.*, 21: 283–287.
Stevenson, F.J., 1959a. *Soil Sci.*, 88: 201–208.
Stevenson, F.J., 1959b. *Science*, 130: 221–222.
Stevenson, F.J., Kidder. G. and Tilo, S.N., 1967. *Soil Sci. Soc. Am., Proc.*, 31: 71–76.
Stevenson, F.J., Harrison, R.M., Wetselaar, R. and Leeper, R.A., 1970. *Soil Sci. Soc. Am., Proc.*, 34: 430–435.
Stevenson, F.J. and Swaby, R.J., 1964. *Soil Sci. Soc. Am., Proc.*, 28: 773–778.
Stewart, B.A. and Porter, L.K., 1963. *Soil Sci. Soc. Am., Proc.*, 27: 41–43.
Tyler, K.B. and Broadbent, F.E., 1960. *Soil Sci. Soc. Am., Proc.*, 24: 279–282.
Walsh, L.M. and Murdock, J.T., 1963. *Soil Sci. Soc. Am., Proc.*, 27: 200–204.
Welch, L.F. and Scott, A.D., 1960. *Soil Sci.*, 90: 79–85.
Young, J.L., 1964. *Soil Sci. Soc. Am., Proc.*, 28: 339–345.
Young, J.L. and Cattani, R.A., 1962. *Soil Sci. Soc. Am., Proc.*, 26: 147–153.
Young, J.L. and McNeal, B.L., 1964. *Soil Sci. Soc. Am., Proc.*, 28: 334–339.

Chapter 12

NITRIFICATION

INTRODUCTION

The term nitrification has been used to mean different things by different investigators, and hence the definition has varied from time to time. The term is defined officially (*Soil Sci. Soc. Am., Proc., 1962*, 26: 311) as "the biological oxidation of ammonium salts to nitrites and the further oxidation of nitrites to nitrates." Alexander et al. (1960) and Alexander (1965) point out that this definition is inadequate since Schmidt (1954, 1960) showed that certain heterotrophic organisms can form nitrate from amino nitrogen compounds. They suggested an alternate definition, namely, "the biological conversion of nitrogen in organic or inorganic compounds from a reduced to a more oxidized state." Both of these definitions are limited to biological oxidations and for that reason are not all inclusive. As is pointed out below, chemical nitrification (chemo-nitrification), at least of nitrite, also occurs to a considerable extent under certain conditions. A further complication is the fact that for decades many practical agriculturalists, and others, have used the term nitrification to mean the formation of nitrates from most any nitrogen source, such as soil, animal manures, organic fertilizers and sewage. The emphasis in such cases is usually on the availability of the nitrogen source without regard to the biochemical or chemical mechanisms by which the nitrate is produced. In this usage ammonification and nitrification are lumped together. The confusion in terminology with respect to nitrification is similar to that which exists with the term denitrification. In the present discussion the official definition will be adhered to for the most part; where a broader use of the term is used it will be obvious from the text.

IMPORTANCE

The importance of nitrification in soils has been repeatedly emphasized over the years ever since, and even before, Schloesing and Müntz (1877) demonstrated that the oxidation is biological in nature, and Winogradsky (1890) succeeded in isolating the bacteria involved. A good nitrifying soil was usually considered as a fertile and productive one. In fact, in the early years of this century soils were commonly tested experimentally for their nitrifying capacity. Many attempts were made to determine if there was a good correlation between nitrifying capacity and crop production. Often there were good correlations but not always. It was found that poor correlations did not downgrade the importance of nitrate nitrogen in crop production but rather that the quantitative needs, and even some of the environmental requirements, or tolerances, of the bacteria may be very different from those of the crop being grown. Mere traces of mineral elements may, for example, be adequate for optimum nitrification, whereas a good field crop may require several pounds per acre of P, S, Ca and Mg. In other cases a grass crop may yield tons of dry matter per acre when grown on a soil too acid for rapid nitrification. Such a crop, as is well known, seems to be able to thrive wholly, or almost wholly, on ammonia nitrogen. Another example might be the failure of a good nitrifying soil to produce large crops following the plowing under of large amounts of carbonaceous residues that immobilize most of the nitrate as rapidly as it is produced. Many other examples might be given.

In recent literature some authors have thrown doubt on the value of nitrification. Alexander (1965) states that it is a "mixed blessing and, possibly, a frequent evil." He bases his conclusion chiefly on the fact that nitrates are easily lost through leaching or as gases by denitrification; and nitrites are chemically unstable. In addition, the acids formed during nitrification may, if not neutralized, form soluble K, Ca, Mg, Mn, P and Al. In extreme cases aluminum toxicity may be encountered. Presumably since most plants can utilize ammonia nitrogen, and some prefer it, nitrate formation is not considered especially essential.

The importance, or lack of importance, that one attaches to nitrification is largely a matter of emphasis that he places on the various observed facts. Although the author admits that there are a few mixed blessings, he considers that on the whole nitrification is a very essential and valuable process. If nitrification in soil could be prevented completely it is doubtful if we could have an agriculture such as we have today, at least not without supplying much of our fertilizer nitrogen in the nitrate form. Some of the reasons for this viewpoint are discussed at the end of this chapter.

Aside from agriculture, microorganisms are of great value in the ammonification and subsequent nitrification of the organic matter in the waters discharged from sewage disposal plants. It is customary in these plants to provide a vigorous aeration system for these contaminated waters, and in this environment an abundant and highly active flora of nitrifiers develops.

Meiklejohn (1953) calls attention to some of the early sources of saltpeter and the biological methods for its production, although at the time it was not known that microorganisms were involved. She states that the value of potassium nitrate was first appreciated when gunpowder came into use in Europe in the fourteenth century. For the next 500 years it was collected chiefly for the manufacture of gunpowder, but also for pickling meat. The usual sources were soils impregnated with animal excrements and kept moist; old walls and the plaster of ruined buildings similarly contaminated; and cellar walls, burial mounds and the earth of old graveyards. In more recent times, she states that old houses in abandoned villages of India, Egypt and elsewhere were valued as nitrate sources. Of course only sites protected from the rain and sun yielded saltpeter. Napoleon obtained a portion of his supply of nitrate by making heaps of earth, manure and chalk inside sheds and watering them with urine or waste water. These piles were either turned at frequent intervals or aerated by means of buried pipes. After two years the saltpeter was extracted with hot water. Taber (1942) states that a similar system was used in the South during the Civil War; some decomposed and oxidized bat guano was also obtained from caves.

NITRIFICATION BY AUTOTROPHIC BACTERIA

Several genera of autotrophic nitrifying bacteria have been described (Meiklejohn, 1953; Alexander, 1965) but only two, *Nitrosomonas* and *Nitrobacter*, are generally considered as being widely distributed and agriculturally important in soils. The present discussion will deal only with these two genera of autotrophs since they are not only the most important but the only ones that have been studied extensively. Fortunately the two genera thrive under essentially identical environmental conditions and can be discussed together quite conveniently.

The bacteria and their nutritional requirements

Both *Nitrosomonas* and *Nitrobacter*, being obligate autotrophs, require no organic source of energy. *Nitrosomonas* obtains its energy by oxidizing ammonia to nitrite, and *Nitrobacter* by oxidizing the nitrite to nitrate. The reactions involved are as follows:

Nitrosomonas: $NH_4^+ + 1\frac{1}{2} O_2 \rightarrow NO_2^- + 2\,H^+ + H_2O + 79$ Cal.

Nitrobacter: $NO_2^- + \frac{1}{2} O_2 \rightarrow NO_3^- + 20$ Cal.

They obtain their carbon dioxide for cell synthesis from the air or from any available carbonate sources present. Our knowledge of the biochemistry of the oxidation processes and intermediates has been reviewed by Alexander (1965). Suffice it to say that such information is very limited.

The nitrifying organisms are motile rods about 1–2 μ in length and half this in width. They make only limited growth even on the best media, and are among the most difficult to isolate in pure culture. They are also very sensitive to unfavorable environments and inhibitors, yet are found widely distributed in cultivated soil. It is only rarely that a soil is found that is free of the organisms, provided it is suitable for general agriculture. Their nutritional requirements include the usual mineral elements in small amounts but no organic compounds are required. Contrary to some reports, we now know that the organisms will grow in media containing no solid substances, such as calcium carbonate that was supposedly needed and regularly used in earlier investigations. According to Alexander (1965) the composition of the autotrophs differs little from that of heterotrophs even though their food supply is very different. Engel and Alexander (1958) observed that *Nitrosomonas europaea* had a generation time of about 11 hours, which is a little longer than required for *Nitrobacter*. In contrast, many heterotrophs will divide in less than one hour.

Ammonia and nitrite supplies

Since the two genera of autotrophs are wholly dependent for their growth energy on the supplies of ammonia and of nitrite it is obvious that the amount of these substances, under optimum growth conditions, largely control the number of autotrophic bacteria and their rate of oxidation of the two substrates. Where soil organic matter is the sole nitrogen source, and soil conditions are optimum for nitrification, all ammonia that is released by decay organisms is quickly converted in a bare fallow soil to the end product nitrate. This does not indicate that either ammonia oxidation or nitrite oxidation is a more rapid process than is ammonification. Instead, it emphasizes the biological stability of soil organic matter. It is so resistant to attack by the hundreds of species of heterotrophs present that the limited amount of ammonia liberated can be nitrified as fast as it is produced. The nitrifiers are, in fact, capable of oxidizing much larger amounts. This can easily be demonstrated by adding an ammonium salt, such as ammonium sulfate. It can also be shown readily by the addition of a protein or other readily decomposable nitrogenous substance that ammonification can proceed far more rapidly than nitrification. Under such conditions ammonia may be liberated at such a fast rate that within two or three days the nitrifiers are completely swamped by the high concentration of ammonia. Several days may elapse before the ammonia is sufficiently sorbed chemically and physically for nitrite and nitrate formation to be in evidence.

Nitrobacter is sensitive to the presence of ammonia even at comparatively low concentrations (Aleem et al., 1957; Broadbent et al., 1957; Tyler and Broadbent, 1960). Where such inhibition occurs considerable nitrite but little nitrate may be formed. In acid soils, where nitrites are unstable, some of the nitrogen may be lost as oxides of nitrogen or as nitrogen gas, as is pointed out in Chapters 11 and 13. Over the pH range of 3 to 7 the nitrite may also react with soil organic matter (Führ and Bremner, 1964a, b; Stevenson and Swaby, 1964; Stevenson et al., 1970) to form stable compounds. Nitrites are known to be inhibitory to the respiration of *Nitrobacter*, as well as to most other bacteria, under acid conditions but only very mildly so in calcareous soils (Tyler and Broadbent, 1960).

Aeration and moisture

Nitrifying bacteria are obligate aerobes and are very sensitive to oxygen deficiency. These organisms do not require large quantities of oxygen, or high partial pressures, if the oxygen is actually in contact with the bacterial cells. The difficulty is that in soils one can never be certain that the rate of diffusion into the finer pores is sufficiently rapid to meet these requirements. Even in well-aerated liquid cultures of many bacterial species it has been demonstrated repeatedly that the oxygen does not always go into solution as rapidly as it is used. In work with a Carrington silt loam Amer and Bartholomew (1951) found that reducing the oxygen concentration from 20–11% had only a slight effect on the rate of nitrification, but a further reduction to 2.1% lowered nitrate production by a half. In many other soils, and under other experimental conditions, it is likely that even with 20% oxygen all parts of the soil might not be adequately supplied with oxygen for optimal nitrification.

The nitrifying bacteria differ little from soil heterotrophs in their moisture requirements and are active over a wide range of moisture down to near the wilting point. The optimum for soil of intermediate texture is in the range of 50–70% of water holding capacity. For very sandy soils it may be a little higher, and for very fine-textured soils a lower percentage may be best. These bacteria are not active at quite as low a moisture level as are some of the heterotrophic fungi and actinomycetes. As the soil moisture level diminishes to near the air-dry condition the bacteria in some unknown way, since they do not form spores, become resistant to desiccation and can remain alive in this desiccated condition for several years.

It is excess moisture that often presents a problem because, as soil water increases, the oxygen supply diminishes. The finer the soil texture the greater the damage produced by excess moisture. Nitrate formation may be largely or wholly prevented and any nitrate previously formed is likely to be lost to the air by denitrification. According to Greenland (1962) nitrification and denitrification can occur at the same time in the same soil if it is rather fine textured. In such soils the macropores may be well aerated while the centers of the larger aggregates are oxygen deficient. Large additions of organic matter, such as a green manure crop, may also increase the oxygen deficiency, especially in the first few weeks when carbon dioxide is being evolved at a very rapid rate.

Temperature

It is a well-established fact that under ideal conditions most biological and chemical reactions are increased 2- to 3-fold for each rise of 10°C over the effective range. At either end of the range the rate of reaction is likely to be greatly reduced. This seems to hold for nitrate formation in soils. Fig.12.1 shows some of the data obtained by Frederick (1956) that illustrate the point. Under his conditions very slow nitrification

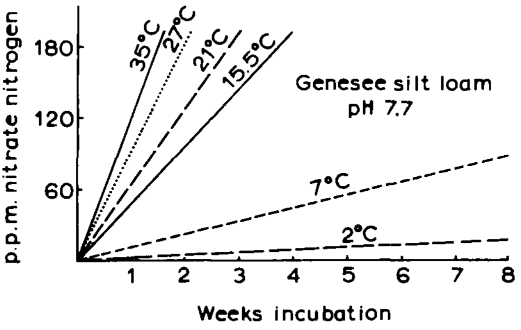

Fig.12.1. Nitrate formation in Genesee silt loam with 180 p.p.m. NH_4-N added, at various temperatures with time. (From Frederick, 1956.)

occurred at 2°C and increased markedly up to 35°C, which was the highest temperature studied. From other studies we know that 35°C was very near the maximum limit of growth and oxidation of the nitrifying bacteria. Tyler et al. (1959) also observed a slow but measurable rate of nitrification in California soils incubated at 3°C. There were indications that *Nitrobacter* is more sensitive to low temperatures than is *Nitrosomonas*, since under these conditions some nitrite accumulated.

Reaction and lime

Nitrosomonas and *Nitrobacter* are probably the most sensitive to acidity of any of the common soil organisms. They grow best at pH values of about 7 to 9 and if the pH drops even slightly below the neutral point their oxidizing activities are considerably curtailed. Since the products of their activities are acids it is a common observation that the rate of nitrate formation often declines with time due primarily to the decrease in pH.

The lower limit of activity varies somewhat with the soil and the native organisms present but is usually near pH 4.5 (Broadbent et al., 1957). In the range of pH 4.5 to 6 nitrate formation proceeds very slowly. This is due chiefly to the effect of acidity on the growth of the bacteria, but as acidity increases the stability of nitrite decreases. Some of the nitrogen may be lost and some may also react with soil organic matter and no longer be available for use by *Nitrobacter*.

The autotrophic nitrifiers respond very favorably to the addition of lime to culture media and to soils. This is usually primarily a pH effect but of course these bacteria use carbon dioxide as their source of carbon and apparently lime is especially suitable for this purpose. In laboratory culture media containing calcium carbonate the bacteria cling rather tenaciously to the solid particles. Some workers (Lees and Quastel, 1946) have believed that the presence of such a solid surface was essential for growth but Goldberg and Gainey (1955) showed that this is not true. In recent years techniques have been developed for growing relatively large quantities of the organisms in solid-free media (Engel and Alexander, 1958; Aleem and Alexander, 1960). The marked response of the nitrifiers to lime is well illustrated by the work of Allison and Sterling (1949) who applied lime to 30 North Dakota soils that had pH values between 6.1 and 7.3. The average increase in nitrate production in 18 weeks, due to lime, was about a third, which is a high value considering the initial pH values of the soils.

Organic matter

Many statements have been made over the years that nitrification is prevented or at least inhibited by organic matter. According to Meiklejohn (1953) such statements may be attributed chiefly to an early paper by Winogradsky and Omeliansky (1899). They found that small amounts of glucose, peptone, asparagine, and sodium butyrate stopped nitrification; larger amounts of urine, broth and sodium acetate did likewise. The supposed inhibiting effect of glucose has received the most attention. It is now definitely established (Meiklejohn, 1951) that if this substance is sterilized by heat in the autoclave the medium is usually toxic because of decomposition products; if sterilized by filters without heat glucose is non-toxic. Meiklejohn (1953) states that peptone is very toxic in laboratory media, and asparagine and sodium butyrate behave similarly. Many other substances could be added to the list because both *Nitrosomonas* and *Nitrobacter* are extremely sensitive organisms. Under natural conditions in soils none of these substances would be present in more than traces, and then only temporarily. The supposed harmful effect of soil organic matter can now be considered as a fallacy.

There are actually some reasons for suspecting that organic matter may furnish growth factors or specific stimulants for nitrification. So far as known to the author, there is no direct proof of this and probably no such unknown organic materials are required. We do know that under natural conditions the most active nitrifying flora are invariably found in environments that are high in organic matter providing that other factors, especially pH and aeration, are satisfactory. We have already mentioned the high activity in sewage waters and in aerobic manure piles. The same is true in soils. The soil scientist who wishes for any reason to inoculate his experimental soil with vigorous nitrifying organisms hunts for the richest garden soil that he can find. And such a soil is the one that has been continuously treated with manure, compost, and possibly green manures. Soils low in fertility and organic matter seldom contain large numbers of nitrifiers.

The favorable effect of organic matter on the nitrifiers under soil conditions can undoubtedly be attributed to factors aside from the need of organic substances for nutrition. In fact there is no evidence that the organisms use any outside sources of organic matter for nutrition. But such organic materials can by chelation and other means continually supply the bacteria with highly available inorganic elements, especially iron. Decayed organic materials also have a high exchange capacity and this means that abundant supplies of Ca, Mg, K and other cations are available. Ammonia, phosphorus and sulfur are also constantly being released for the use of these organisms. Considering that ammonia nitrogen is needed in large amounts, and the others in only small amounts, it is entirely possible that ammonia release is the most important. Organic matter also serves as an ideal buffer for sorption of the nitrous and nitric acids as they are produced.

The depressing effect on nitrate formation of highly carbonaceous residues, added to soils, should be mentioned here even though discussed elsewhere in this book (Chapter 6). The lack of nitrate accumulation in soils treated with such materials was at one time attributed to their depressing effect on the microorganisms. There is little or no evidence in support of this viewpoint. Rather, it would seem that lack of nitrite and nitrate formation under such conditions can be attributed primarily to the competition for ammonia by the mass of rapidly growing bacteria, fungi, actinomycetes, and crop, if present. The autotrophs would be poor competitors for the very limited supply of ammonia, and if they did get a portion of it, the heterotrophs would not allow nitrate to accumulate.

Grassland soils

Many workers have observed that crops depress the mineralization of nitrogen. This subject has been reviewed by a number of workers, including Goring and Clark (1948), Theron (1951), Harmsen and Van Schreven (1955) and Soulides and Clark (1958). Decreased mineralization is usually attributed to the increased immobilization of nitrogen by the rhizosphere population brought about in part by root excretions but more by the mass of root debris that accumulates with increased age of the plants. This is well illustrated by Fig.5.1 taken from the paper by Goring and Clark.

Closely related to this phenomenon is the further observation that in acid grassland soils there is often an apparent accumulation of ammonia nitrogen or a retardation of nitrate production. At the Rothamsted Experimental Station, England, the content of NH_4-N in grassland soils during a 3-year period ranged from 4.6 to 6.6 p.p.m., whereas NO_3-N did not exceed 2 p.p.m. Since most microorganisms and higher plants can utilize ammonia as readily, or more readily, than they can nitrate, it has been a bit puzzling to explain the relatively higher percentages of ammonia than of nitrate in grassland soils. This subject has been reviewed by the workers mentioned in the preceding paragraph, and more recently by Brar and Giddens (1968). The views of Theron have in recent years received the most consideration. He believed that plant roots secrete specific substances that exert a bacteriostatic effect on nitrifying organisms. In my opinion this is very improbable and certainly not proven. Soulides and Clark (1958) concluded that there exists some distinct factor in grassland soils that delays the microbiological oxidation of ammonia. This conclusion can be interpreted as possibly being in support of the hypothesis of Theron.

Studies made by Brar and Giddens with an acid Bladen grassland soil (pH 4.6 to 4.8) that was a poor nitrifier led them to conclude that acidity and the resulting low population of nitrifiers was the cause of low nitrification. Nitrification was improved by liming but not by extraction of possible toxic substances, as hypothesized by Theron. Likewise, Molina and Rovira (1964) could find no evidence for a rhizosphere inhibition.

None of the suggested explanations for limited nitrate formation in grassland soils seems to explain adequately this phenomenon. Under various soil conditions one or more of the ideas advanced may play a role but in the author's opinion none of them has wide application. I would suggest that the key to the explanation lies in the scarcity or absence of nitrous acid in acid soils. Obviously, the amount of nitrate that is formed is dependent directly upon the amount of the intermediate (nitrous acid) that is present or being formed. In the absence of nitrous acid there certainly can be no nitrate formation by *Nitrobacter*. Nitrous acid deficiency may be the result of: (1) a soil pH (below about 4 to 4.5) that is too low to permit *Nitrosomonas* to grow; (2) rapid decomposition under acid soil conditions of any nitrite that does form; and (3) reaction of nitrous acid with lignin and possibly other organic compounds to form nitroso compounds and gaseous products, as shown by Stevenson and Swaby (1964), Führ and Bremner (1964a,b), Edwards and Bremner (1966), Bremner and Nelson (1968) and Stevenson et al. (1970). This last-named reaction occurs over the range of pH 3 to 7, but decreases as neutrality is approached. It would undoubtedly be favored by the presence of masses of grass root debris.

It is in the more acid grassland soils that the ammonia–nitrate ratio is widest. This is in harmony with expectations based on the facts mentioned above. As the pH increases, the nitrate level also commonly increases because of: (1) favorable effect of higher pH on both *Nitrosomonas* and *Nitrobacter*; (2) greater stability of nitrites; and (3) reduced rate of reaction of nitrous acid or nitrites with lignin. Meanwhile, ammonia formation can proceed more or less normally at any soil pH, and the ammonia can accumulate if not utilized by higher plants and microorganisms, and not oxidized to nitrites and nitrates. There is little reason for considering wide ammonia–nitrate ratios in acid grassland soils as an enigma; such ratios are to be expected at low pH values. If these ratios are commonly wider in grassland soils than in cultivated soils of the same pH, then the tendency of nitrite to react with lignaceous materials (grass root debris) would seem to be emphasized.

Cell-free nitrification

Cell-free *Nitrobacter* extracts were shown by Aleem and Alexander (1958) to be able to oxidize nitrite to nitrate. Subsequently, Aleem and Nason (1959) reported that the nitrite-oxidizing activity resided in a cytochrome-containing particle designated as nitrite oxidase. Nason (1962) states that "their data implicated the action of the nitrite oxidase system to involve the enzymatic transfer of electrons from nitrite to molecular oxygen via cytochrome c- and cytochrome oxidase-like components." Iron is specifically required in the oxidation process.

According to Nason, cell-free extracts of *Nitrosomonas* have been shown to bring about the oxidation of hydroxylamine but not of ammonia to nitrite.

The demonstration that extracts of *Nitrosomonas* and *Nitrobacter* can under certain well-defined conditions bring about nitrification is of much biochemical interest but, so far as known, not of practical importance. Such enzymatic studies constitute very interesting basic research.

NITRIFICATION BY HETEROTROPHIC MICROORGANISMS

The production of either nitrite or nitrate from ammonia, or other reduced forms of nitrogen, is brought about by a considerable number and variety of heterotrophic microorganisms. Alexander (1965) lists several kinds of bacteria, actinomycetes and fungi that have been shown to produce at least small amounts of these two compounds. Among these is one anaerobic bacterium, *Clostridium butyricum*, which can oxidize elemental nitrogen to nitrate; this is certainly an unusual transformation. Only one of various types of microorganisms, *Aspergillus flavus* and related species, has been shown to form nitrates in large amounts. Eylar Jr. and Schmidt (1959) reported that this organism produced 90 p.p.m. during a period of two weeks when grown in a glucose–peptone medium. Hirsch et al. (1961) observed little nitrite production from ammonium by *A. flavus* but the fungus formed in excess of 100 p.p.m. of nitrate nitrogen.

Various reduced forms of nitrogen, including amines, amides, N-alkylhydroxylamines, oximes, hydroxamic acids and aromatic nitro compounds, serve as substrates for nitrite, but not for nitrate, formation by various individual organisms (Doxtader and Alexander, 1966). Nitrite yields varied from a few to 190 p.p.m. Cell extracts of a *Fusarium* were able to convert an oxime into nitrite.

Our knowledge of the biology and biochemistry of the heterotrophic nitrifying organisms is very meager. The list of genera and species is so large, the substrates and oxidized products so varied, and the quantity of end products produced by the organisms other than *A. flavus* so small that the problem seems almost overwhelming. These organisms fit into no specific taxonomic pattern; one of them is not even an aerobe. This extreme heterogeneity would seem to suggest that the ability to oxidize reduced forms of nitrogen is not only widespread but merely an incidental phase of their metabolism. Whether nitrites or nitrates are detected in the culture medium by the researcher may be largely a matter of chance. Since essentially all nitrogen present in living cells is there in the reduced form, it would seem illogical to suppose that the nitrogen that is used in cell formation is first oxidized and then reduced to cellular material. Instead, it would seem more likely that the nitrate is a discarded waste product. In line with this idea is the observation of Schmidt (1960) that nitrate accumulated in *A. flavus* cultures only after the time of maximum growth. Doubtless only under special conditions does such nitrate excretion occur.

All of these organisms, sofar as known, secure their energy for growth exclusively from organic substances. In other words they are true heterotrophs. This necessity for an organic source of energy, such as a sugar or protein, greatly complicates their isolation in pure culture and the study of their biochemical transformations. The small amounts of nitrite or nitrate produced and the uncertainty of just what conditions are conducive to the formation of even these small amounts adds to the research difficulties.

A. flavus is a common species that has been isolated from soils from all over the world, and appears to be about the only heterotroph that produces comparatively large amounts of nitrate. Schmidt (1960) found that a reaction of pH 6.5 or above was required for this organism during the early stages of growth. Compounds ranging from ammonium to casein and animal manures were oxidized to nitrate, which accumulated if the reaction was favorable and more nitrogen was present than needed for cell synthesis.

Attempts were made by Schmidt to determine the possible significance of *A. flavus* as a soil nitrifier. The addition of a pure or mixed culture to several sterilized soils resulted in no nitrate production. When a number of plant substances were added to quartz sand, followed by sterilization and inoculation with *A. flavus*, no nitrate was formed from barley, oat and wheat straws, but approximately 90 and 108 micrograms of nitrate nitrogen per gram of residue was formed in two weeks from alfalfa and manure, respectively. When *A. flavus* was added to soil containing either alfalfa or manure and streptomycin to eliminate the autotrophic nitrifiers, no nitrate was formed in sterilized or unsterilized soil. This is very surprising since these materials apart from soil provided a nitrifiable substrate for the organism. It was shown that the fungus grew normally in the non-sterile soil and was not harmed by the streptomycin.

Our present knowledge of the heterotrophic nitrifiers leads to the conclusion that they are not responsible for much of the nitrate commonly formed in soil. They may actually oxidize more reduced nitrogen than we suspect, but if they do, they utilize most of it in their own growth processes. More information is much needed but in the meantime we must still consider that the two autotrophs are primarily responsible for the biological oxidation of ammonia and nitrite.

CHEMICAL NITRIFICATION (CHEMO-NITRIFICATION)

The possibility of nitrate formation in soils by strictly chemical oxidation is seldom mentioned, or barely so, in texts or review articles. This is not surprising since studies of this subject are limited and few quantitative data are available. The oxidation of ammonia to nitric acid is a long-established commercial process used in the production of this acid for fertilizers or other purposes. It is of interest to consider the main steps involved since some of the same reactions occur in soils. Krase (1932) outlined the commercial process.

A mixture of ammonia and air (or oxygen) is passed through heated fine-mesh, platinum gauze. This converts 90–95% of the ammonia in the gas to nitric oxide, which is further oxidized to nitrogen dioxide. The gases are then passed into absorption towers where they are scrubbed with water, converting the nitric dioxide into nitric acid. The following reactions occur:

$$4\,NH_3 + 5\,O_2 \rightarrow 4\,NO + 6\,H_2O \qquad (1)$$

$$2\,NO + O_2 \rightarrow 2\,NO_2 \qquad (2)$$

$$3\,NO_2 + H_2O \rightarrow 2\,HNO_3 + NO \qquad (3)$$

The NO of reaction (3) is further oxidized in the scrubbing towers according to reaction (2). The final product of the three reactions is an acid of 45–50% nitric acid content.

Oxidation of ammonia

Waksman and Madhok (1937) in their review of the early literature mention a number of investigators who have reported that ammonia can be oxidized in solution to nitrite by chemical or more often photochemical methods. Oxidation beyond the nitrite stage was seldom, if ever, observed by these early workers. Claims by a few Indian workers, especially Dhar and associates, that this occurs photochemically in soils were discounted. Fraps and Sterges (1935), Waksman and Madhok (1937) and Waksman et al. (1937)

found no evidence for photochemical oxidation in soil in the presence of either sunlight or ultra-violet light. Waksman (1932, 1952) states that the quantities of nitrite and nitrate formed by chemical agencies are insignificant and of little importance in soils.

Mortland (1958) briefly reviews the subject of nonbiological oxidation of ammonia in soil and concludes that the importance of this process in soil is not completely known. He states that although many experiments have failed to show appreciable nonbiological oxidation, "it is possible that such reactions may occur in soils, though perhaps to a small degree, under the influence of such radiations as sunlight, cosmic rays, and natural radioactivity." Russell (1961) concludes that there seems to be little doubt that ammonia can be oxidized to nitrite in solution photochemically, but the importance of photo-oxidation to nitrite even in tropical soils, where it can only be a surface phenomenon, is still undecided.

New experimental data and radical changes in agricultural fertilizer practices during the past two decades have in the writer's opinion made necessary some marked modifications in our evaluation of chemical nitrification in soils. There is still no evidence that would seem to change appreciably the views of Waksman, Mortland, and Russell, as expressed above, with regard to chemical and photochemical oxidation of ammonia. There are, however, very good reasons for believing, contrary to the earlier views, that the chemical oxidation of nitrites to nitrates is an important reaction in acid soils where nitrite is being formed by whatever mechanism. Admittedly, direct quantitative data are still inadequate, but what is available plus indirect data and observations are convincing. Let us consider some of the reasons for this statement.

Oxidation of nitrous acid

Allison and Doetsch (1951) conducted several experiments in Warburg vessels in which sodium nitrite was allowed to react in air in solutions buffered with mixtures of phosphoric acid and potassium salts to give pH values in the range of 1.6 to 6.0. In acid solutions nitrous acid, or its salts, decompose as follows:

$$3\,HNO_2 \rightarrow HNO_3 + 2\,NO + H_2O \qquad (4)$$

In the presence of air the NO thus formed is oxidized to NO_2 as shown above in reaction (2). Since water is present, the NO_2 reacts with it according to reaction (3) if the water is hot and according to (5), shown below if the water is cold.

$$2\,NO_2 + H_2O \rightarrow HNO_3 \rightarrow HNO_2 \qquad (5)$$

Presumably, in Warburg vessels, maintained at 30°C, both reactions (3) and (5) would occur. In either case any NO or HNO_2 formed would be subject to further oxidation as in (2) or (4).

In Fig.12.2 is shown the uptake of oxygen from air by nitric oxide evolved from

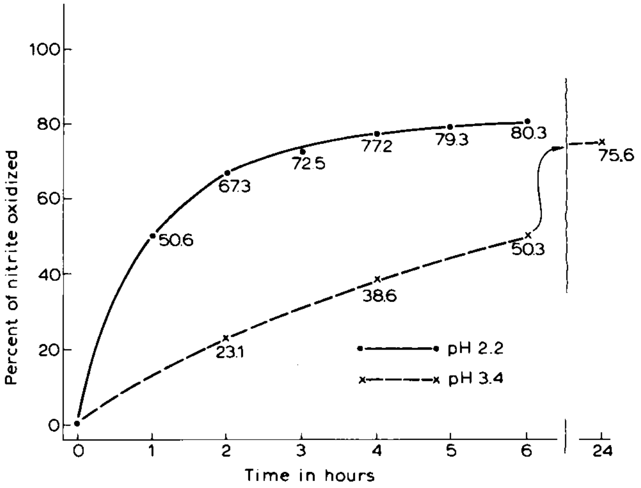

Fig.12.2. Oxygen uptake from air by nitric oxide evolved from sodium nitrite at pH 2.2 and 3.4. (Drawn from data of Allison and Doetsch, 1951.)

sodium nitrite added to phosphate buffers of pH 2.2 and 3.4. To oxidize all of the nitrite added in these experiments to nitrate would require 324 cm^3 of O_2 per respiration vessel. Fig.12.2 shows that approximately half of the oxygen required for complete oxidation of the nitrite had reacted in one hour, and 81% in 6 h at pH 2.2. The corresponding figures for pH 3.4 were 22 and 49%, respectively; after 24 h at this pH the oxygen uptake was 75%. Other experiments, conducted at pH 2.9, showed that at nitrite concentrations as low as 25% of those used in the preceding experiments the oxygen uptake values per unit of nitrite added were approximately the same as at the higher concentration of nitrite.

The oxygen uptake from air by nitric oxide evolved from sodium nitrite added to phosphate buffers of pH 1.6 to 5.2 is shown in Fig.12.3 for three time periods. No measurable amount of oxygen was utilized during a 24-h period at pH 5.2 or higher but as the pH decreased the oxygen uptake increased rapidly as shown in Fig.12.2.

These data in Fig.12.2 and 12.3 leave no doubt that chemical nitrification of nitrites to nitrates occurs readily in 1% potassium phosphate solutions that are more acid than about pH 4.0. In soils it has been shown (Stevenson and Swaby, 1964; Führ and Bremner, 1964a; Stevenson et al., 1970) that a portion of any nitrous acid formed can react with soil organic matter, especially at the lower pH values, but a considerable portion of it decomposes to liberate NO. Quantitative data on the extent of these reactions under a wide variety of soil conditions have not yet been reported. Mortland and Wolcott (1965) and Mortland (1965) have shown that NO can penetrate the interlamellar surfaces of montmorillonite and in the presence of air it is oxidized at a rate dependent upon its diffusion to the edge of the particle. All of the nitric oxide was oxidized in 24 h or less. These data leave no doubt that nitrite undergoes nitrification in soils very much as in phosphate buffer solutions, except possibly to a lesser extent since a portion of it is fixed

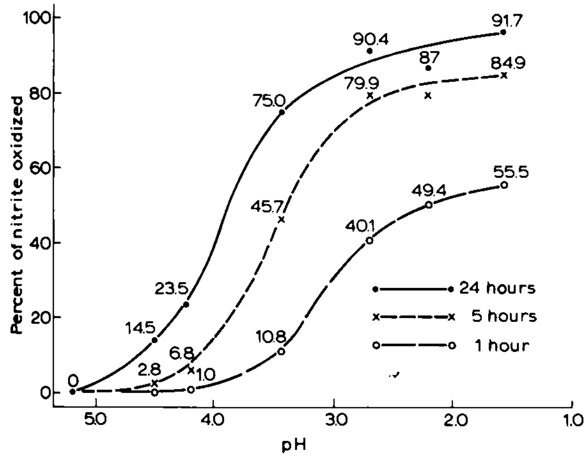

Fig.12.3. Oxygen uptake from air by nitric oxide evolved from sodium nitrite at various pH values. (Drawn from data of Allison and Doetsch, 1951.)

by combination with lignin. It is noteworthy that the portion sorbed in the clay was oxidized completely within 24 h much as occurred in buffered solutions.

Smith and Clark (1960) observed that in a solution buffered at pH 4.0–4.5 to which 500 mg nitrite nitrogen per 100 ml was added 12, 22 and 36% of the nitrite nitrogen was oxidized in a helium–oxygen atmosphere to nitrate in 2, 6 and 24 h respectively. At pH 5.6 only 4% of the nitrite was oxidized to nitrate in 24 h. Where nitrite nitrogen was added to a Ft. Collins loam (pH 4.2–4.7) 55% of it was oxidized to nitrate in 18 h; the corresponding value for a low organic matter Durham soil (pH 4.9) from North Carolina was 80%. In these experiments where any gases evolved were analyzed by gas chromatography it is of considerable interest that neither NO nor NO_2 was encountered where adequate oxygen was present. This finding is in harmony with the results of Mortland and Wolcott (1965) mentioned above, and with the statement made repeatedly in the literature that NO is absorbed so rapidly and completely by soils that little of it escapes to the atmosphere. When once absorbed, it is oxidized fairly readily to NO_2 and NO_3.

Reuss and Smith (1965) added $NaNO_2$ to a Bath soil (pH 4.6) and a Walla Walla soil (pH 5.6) and observed that after 24 h about 25% of the nitrogen had been oxidized to nitrate in the more acid soil and 14% in the Walla Walla soil. Experiments in steam-sterilized and non-sterilized soils gave identical results.

Another experiment was conducted by Reuss and Smith in which they used a cation exchange resin buffered at pH 5.2 instead of soil. Fig.12.4 shows the results obtained with and without an alkaline $KMnO_4$ trap to catch the NO, NO_2 and CO_2. The rate of chemical nitrification was even more rapid here than in soil, with 44% of the added nitrite being oxidized in 1 day and 70% in 4 days. Where the oxides of nitrogen were removed as

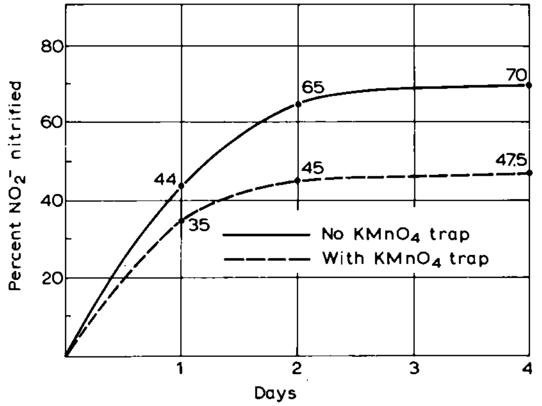

Fig.12.4. Chemical nitrification of sodium nitrite in a cation exchange resin buffered at pH 5.2 and exposed to a helium–oxygen atmosphere. $KMnO_2$ absorbs released NO and NO_2. (Redrawn from Reuss and Smith, 1965.)

formed, and thus prevented from going to nitrate, the nitrate formed was considerably less, as would be expected. Where the atmosphere was devoid of oxygen, only traces of nitrates were formed. The rate of nitrate formation is a little more rapid at this pH than might be expected from the data in Fig.12.3.

Importance in soils

How important is chemical nitrification in soils? Although present evidence indicates that chemical oxidation of ammonia in soils occurs to only a minor extent, if at all, recent researches have definitely established that chemical oxidation of nitrites can and does occur more rapidly than biological oxidation wherever nitrites are present in very acid soils. It follows then that the importance of chemical nitrification is dependent primarily on the extent to which nitrites or nitrous acid are formed in, or move into, soils of pH values where chemical oxidation can occur. As stated above, this critical pH value is near 5 to 5.2, or a little lower for very rapid oxidation.

The importance of chemical oxidation of nitrites cannot be judged by whether nitrites accumulate in quantity in soils. Actually, we know that the more favorable the conditions are for nitrites to accumulate, the less likelihood there is of chemical nitrification so long as the soil environment remains constant and the nitrites remain where formed. They are, however, free to move with the soil water and if the movement is into a soil of pH 5 or less there may be a rapid chemical oxidation to nitrates. For this reason it is important to know to what extent, and under what conditions, nitrites do accumulate. Many investigators have observed such accumulation but only a few representative observations need to be given.

Fraps and Sterges (1930) in studies with several Texas soils that had received $CaCO_3$ found 6 to 98 p.p.m. of nitrite nitrogen after an incubation period of 4 weeks; where 500 p.p.m. of nitrogen as ammonium sulfate was added, 42 to 226 p.p.m. of the added nitrogen accumulated as nitrite. The nitrites usually persisted for several weeks. In one soil, 510 p.p.m. nitrite nitrogen was present after a 4-week incubation and 450 p.p.m. of this was still present after 9 weeks. Incidentally, Fraps had much earlier attributed this lack of nitrate formation to the injurious action of ammonia on *Nitrobacter*, a fact which has been verified repeatedly, and especially emphasized in recent literature.

Nitrite accumulation is also often observed following the addition of large amounts of succulent, nitrogenous green manures, especially legumes, to soil. Smith (1964) found up to 90 p.p.m. of nitrite nitrogen in a Red Bay sandy loam from South Carolina that received 1% alfalfa and $CaCO_3$, and was incubated for several weeks. Maximum nitrite was found in the period of 10 to 20 days, depending on experimental conditions. In one experiment nearly all of the nitrite had been oxidized within 20 days. The ammonia released from the alfalfa increased the pH from 6.8 to 7.4 but after 6 weeks it had returned to the original value. Obviously the nitrite accumulation can be attributed primarily to the free ammonia liberated at this pH, as Fraps suggested. As it was sorbed and dispersed in the soil the *Nitrobacter* were no longer inhibited.

The addition of anhydrous ammonia, aqueous ammonia, urea, or any material that supplies, or liberates, large amounts of ammonia in a localized area often so interferes with the nitrate-producing organisms that nitrites accumulate. Concentrations of 100 or more p.p.m. have been found frequently. When anhydrous ammonia is injected into a soil it may almost sterilize the soil at the point of application. After its sorption by the soil is complete there is a decreasing concentration gradient outward from the point of application. Biological oxidation to nitrite and nitrate proceeds normally at the periphery of this ammonia zone and gradually moves inward if the pH is satisfactory for the bacteria. It usually is sufficiently high initially, at least, because the unionized ammonia raises the pH; as it is oxidized the pH decreases. Any nitrite formed biologically in a soil of pH 5 or less, or any that is leached into such a zone, may then undergo rapid chemical oxidation, as already pointed out. The opportunities for this in our southern soils are very great, for many of these that have been heavily fertilized have very acid subsoils, even though the surface soil pH may have been maintained by frequent liming.

Ammonia oxidation to nitrite and nitrate is proceeding at all times in most cultivated soils but in such soils nitrite may not be detected. This does not prove that chemical nitrification of the nitrite is not occurring. If the pH is appreciably above pH 5 in both the surface soil and subsoil, certainly chemical oxidation would not be indicated. If it is near this critical value it is quite possible that some nitrite could be oxidized chemically. This could occur in a soil that has local zones of varying acidity, such as might result from liming followed by poor mixing, or following the addition of green manures or other nitrogenous organic matter. It is also well to bear in mind that there are numerous heterotrophic nitrifiers that live in soils that are too acid for the autotrophs. Whether they play any significant role in nitrite formation in acid soils is unknown at the present time.

Although this discussion emphasizes some of the possibilities, often overlooked, with regard to chemical nitrification, it is still true that biological nitrification is the main oxidation channel except in special situations. In general, chemical oxidation of nitrites begins at about the pH level that autotrophic bacterial oxidation ceases, or is at a minimum. However, in some soils there is an overlapping of these processes in the range of pH 4.5 to 5.2. This fact may possibly be of considerable importance because many soils with low cation exchange capacities do have acidities in this range between periods of liming, or in local zones.

SOME PRACTICAL CONSIDERATIONS

Agriculturalists have over the years placed great emphasis on nitrification, as is pointed out above. The main reason for this is that prior to about 1925 nearly all agronomists considered that nitrate was almost the only form of nitrogen assimilated by plants, with the possible exception of the grass family that was thought to be able to utilize ammonia. The bulletin by Tiedjens and Robbins (1931) did much to correct the early erroneous ideas. Now the pendulum has swung far in the opposite direction and more and more emphasis is being placed on the preferential use of ammonia by many or most forms of plant life, especially microorganisms. Some practical uses, benefits, and problems involving the nitrifying organisms, are discussed below.

The nitrification test for nitrogen availability

There has long been much interest in methods of testing soils for their ability to supply available nitrogen to crops. Field and greenhouse experiments give the most accurate values, but vegetative tests do not meet the needs. They are too expensive and time-consuming. A quick chemical test would be excellent if it met the requirements. A few have been suggested, but they have not yet met with sufficient favor to be widely used. The chief difficulty with quick tests is that they tend to overemphasize the nitrogen that is immediately available rather than give a fair idea of the nitrogen that the microorganisms can release over an entire growing season. Researches have shown that there is usually a fairly close correlation between total soil nitrogen and the nitrogen supplying power of the soil, and some use has been made of this fact in estimating nitrogen supplies from the soil, and fertilizer needs. Values obtained by this method may not be as accurate as desired because they are affected to a considerable extent by the recent cropping and fertilization history of the soil. Harmsen and Van Schreven (1955) and Harmsen and Kolenbrander (1965) have presented extensive reviews of work done along these various lines.

The nitrification test is the one that has been most widely used. As perfected by workers at the Iowa Experiment Station, a 10-g sample of soil is mixed with vermiculite, incubated for 2 weeks at 35°C, and the nitrates extracted and determined. A series of papers by Fitts et al. (1953, 1955), Hanway and Dumenil (1955) and Stanford and

Hanway (1955) gives the essential features of the method. One of the main requirements in the use of the method is that the laboratory results be calibrated against actual crop yield data obtained under field conditions. Without such a standardization the nitrification data bring out very well the soil differences so that a number of soils under test can be placed in a meaningful order, but the results alone do not serve as a basis for recommendations for specific amounts of nitrogen fertilizer. This biological test is usually considered to be the best that has been proposed but such data cannot be considered as very quantitative. A host of other factors, especially the weather, often increase or decrease the actual amount of available nitrogen that will be released by microorganisms during a long growing period.

In the absence of applied nitrogen, Robinson (1968) observed a close correlation between mineralizable nitrogen and crop yields in African cultivated soils. Mineralizable nitrogen correlated more closely with total nitrogen than with carbon, as was to be expected. He concluded that the mineralizable nitrogen value, determined on soil samples incubated for 6 weeks followed by air drying for 3 weeks, provided a good index of available nitrogen that may be used to predict crop yields.

Some of the data of Allison and Sterling (1959), shown in Fig. 12.5, illustrate the rate of nitrate formation from soil organic matter over a 161-day incubation period. All of these soils were from the same experimental area and with one minor exception had received no fertilizers or animal manures during the 33-year period from original virgin condition. The soil is described as a Cheyenne fine sandy loam. The cropping system consisted primarily of various rotations of corn, small grains, and fallow. Crop yields were

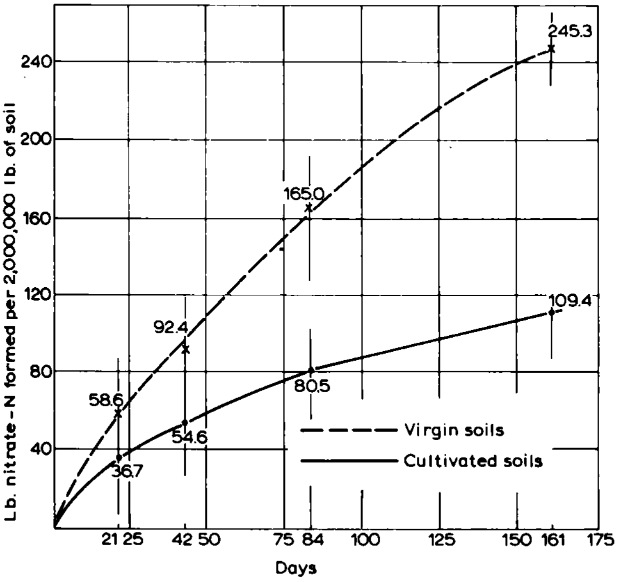

Fig. 12.5. Nitrate-nitrogen formed from soil organic matter during various incubation periods. (Redrawn from Allison and Sterling, 1949.)

not large because the annual rainfall was only about 15 inches. It will be noted from Fig.12.5 that the three virgin soils continued to release nitrogen at only a moderately declining rate during the 161-day incubation period. In contrast, the decrease in rate of release from the 27 cultivated soils after the first month was marked. This illustrates the extent to which previous soil treatment affects the nitrification test for available nitrogen. The time of incubation is also a major factor. When the test is conducted for only 14 days, as is customary, it will be noted from Fig.12.5 that the nitrates formed represent only a small fraction of what might be formed during a 6-month period. Even though the pH of these 30 soils ranged between 6.1 and 7.3, the addition of $CaCO_3$ increased nitrate formation markedly, especially at the longer incubation periods. Under the most ideal conditions an average of 2.7% of the soil nitrogen was oxidized to nitrates in 42 days and 8.7% in 186 days. These high laboratory values would not, of course, be obtained under field conditions.

Considerable use has also been made of the nitrification test as a means of judging the availability of the nitrogen in various organic fertilizer materials (Rubins and Bear, 1942) and in some of the newer synthetics, especially urea formaldehydes. In such tests the incubation period is usually for a considerably longer period than that used in soil tests.

Chemical tests for nitrogen availability

In recent years considerable attention has been given to the development of satisfactory nonbiological tests for available nitrogen. Keeney and Bremner (1966) compared several suggested methods. Nitrogen extraction with boiling water and potassium sulfate provided an index of soil nitrogen availability that was about as good as incubation methods that yield either nitrate under aerobic conditions, or ammonia under waterlogged conditions. Incidentally, this latter method, where ammonia is measured, usually gives about as satisfactory results as the nitrification test and its use in soil testing is likely to increase (Sims et al., 1967; Sims and Blackmon, 1967).

A method was proposed by Richard et al. (1960) in which the nitrate-nitrogen present in the soil is reduced and determined simultaneously with that released as ammonia by digestion with 0.25 N H_2SO_4. The method gave higher correlation with nitrogen uptake by corn than methods based on nitrification rates, total nitrogen or organic matter, and growth of *Aspergillus niger.*

Recent work reported by Stanford and associates (Stanford, 1968a,b, 1969; Stanford and Legg, 1968; Stanford and DeMar, 1969, 1970; Stanford et al., 1970) is throwing much light on the nature of organic nitrogen in soil and the rate at which fertilizer nitrogen becomes incorporated into soil organic matter complexes. As a result of these studies, a chemical method for determining nitrogen availability indexes has been proposed that appears to be satisfactory but slow. It involves the extraction of a soil at 121°C in an autoclave with a dilute solution of calcium chloride (0.01 molar) for a 16-h period, followed by distillation of the nitrogen. Incidentally, these studies indicate that ^{15}N that reaches the soil in the form of crop residues becomes incorporated into newly-formed complexes, similar to those already present in the soil, much more rapidly than has previously been supposed. This conclusion is based on the finding that the percentage removal of total and ^{15}N-labelled nitrogen were almost the same when soils previously treated with tagged residues were subjected to extraction and distillation as outlined above.

Effects of fertilizers, manures and pesticides

The nutrient effects of inorganic fertilizers on *Nitrosomonas* and *Nitrobacter* are limited largely to the ammonia that they supply directly, as in ammonium salts, or indirectly, as in urea or organic materials. Ammonia is of course the chief food of the autotrophic nitrifiers and it can speed up their growth if soil conditions are favorable and the ammonia is not present in too high concentrations. Most common organic materials, as pointed out above, also have a favorable effect on these bacteria. Although they do not utilize the energy that they supply, animal manures and other organic residues undoubtedly improve the environment in which the bacteria live. The mineral needs of these organisms are so small that it is unlikely that they could be appreciably benefitted by the supply of phosphorus and potassium added as commercial fertilizers. Organic materials might supply highly available chelated minor elements that would stimulate growth of the autotrophs but there is no proof of this.

The autotrophic nitrifying bacteria are more sensitive to unfavorable conditions in the soil than are most other common soil microorganisms. This raises the question as to the extent to which they may be killed by additions of our common fertilizers. Such materials, if high in soluble salts or if they are highly reactive substances, can kill some or most of the organisms in a restricted area where the fertilizer is highly concentrated. Anhydrous ammonia is probably the worst offender. The organisms that are an inch or more away from these chemicals are unaffected and as the chemical is sorbed, diluted, or transformed, they quickly spread into the affected area. The result is that none of the fertilizer materials in common use, and supplied at normal rates, are likely to have much direct harmful effect on the soil as a whole for more than a few days. The main exception to this statement is the effect on pH, discussed below.

Where nitrogen is supplied to soils in granular form the effects on the soil and microorganisms are likely to be magnified in the immediate vicinity of the granule. Hauck and Stephenson (1965) state that "large granules, high rates of N application, low soil buffer capacity, as well as an alkaline pH of the immediate granule environment, may lead to nitrite accumulation, even in acid soils." In some soils, considerable nitrite was present for as long as 24 days. Where urea was added to an acid soil, nitrite accumulated and nitrogen losses occurred.

Some fertilizers raise the soil pH, others lower it, and whether the effect is considered beneficial or harmful is largely determined by the soil and to a lesser extent by the crop. Most fertilizers are so compounded as to be classed as neutral but even such materials usually lower the soil pH because they increase yields. Plants, apart from fertilizers, lower the pH because their ash contains more bases than acids (Allison, 1931). The most acid-producing fertilizers are those of the type of ammonium sulfate which, when oxidized, yield both nitric and sulfuric acids. Ammonium nitrate is a little less acid because nitric acid is the sole end product and it may be completely removed by the crop. Other fertilizers, such as sodium nitrate and calcium nitrate may exert some basic effects through the cations supplied. Anhydrous ammonia is unusual in that it may raise the pH locally as high as 9 to 9.5 at the point of application but if it is oxidized to nitric acid there is a marked acidifying effect. None of these materials may exert a major effect in one year but the accumulative effect may lower the pH of poorly-buffered soils to below the critical level (pH 4.5 to 5.0) for the autotrophic nitrifiers. All of these acidifying effects are exactly what is needed if a highly alkaline soil is being fertilized.

The pesticides, including insecticides, herbicides, nematocides and fungicides, now include a very large number of chemicals. Some of these products are so new that their effects on the soil population have not been adequately determined. No attempt will be made to evaluate the many studies that have been made. A few general statements will suffice. The fumigants, which penetrate throughout the soil in gaseous forms, commonly kill many or most of the nitrifiers but after the gases have disappeared into the atmosphere the nitrifiers that were left slowly repopulate the soil. The chief damage, if any, is likely to result from the necessity for the crop that follows to exist for a time exclusively on ammonia nitrogen. Most of the other pesticides are less harmful to the autotrophs, and little effect on nitrate formation is likely to be in evidence. This is chiefly because they are applied in comparatively small amounts, and many of them only to the foliage. Only a small amount comes in contact with the soil and then with only a fraction of it. Except for fumigants, there are only local effects at most, and repopulation of the affected areas takes place readily.

Specific inhibitors

There has been considerable interest in recent years in the possibility of applying chemicals to soils that will prevent or greatly retard nitrification for a period of a few weeks. The main interest in such a substance centers around the possibility of reducing nitrogen losses. Alexander (1965) lists a large number of compounds that have been shown to be inhibitors of one or both steps in the nitrification process. Most of these compounds are for one or more reasons not suitable for general use.

Any compound used as an inhibitor must be effective against both *Nitrosomonas* and *Nitrobacter* and be non-phytotoxic. From the practical standpoint it should be effective in low concentration, be suitable for use in fertilizer mixtures, be moderately priced, and present no health hazards for livestock or humans.

The compound that has received the most attention, and which seems to meet the above requirements better than any other investigated, is 2-chloro-6-(trichloromethyl) pyridine, suggested by Goring (1962a,b). He states that the chemical apparently kills the nitrifying bacteria. In moist soils it is highly sorbed by organic matter but not appreciably by the clay fraction. The minimum concentration of the chemical in soil required to delay ammonia oxidation for 6 weeks is in the range of 0.05 to 20 p.p.m. Expressed as percent of the ammonium or urea nitrogen in the fertilizer the minimum concentration is at least 0.125% for band applications and 2% for broadcast applications. When used with aqua ammonia, 0.125 to 0.5% was effective. Decreased effectiveness of the chemical caused by volatilazation may be experienced when treated fertilizers are broadcast and remain on the soil surface for a considerable time.

A nitrification inhibitor that is fully effective would be expected to: (1) increase efficiency in the use of nitrogen fertilizers, especially on coarse-textured soils where rainfall is high, or extensive irrigation is practiced; (2) make more feasible the practice of fall applications of ammonia; (3) make less critical the time of nitrogen fertilizer applications and the need for split applications; and (4) reduce nitrogen losses that may occur via nitrite decomposition or reaction with organic matter. Whether the benefits to be expected are sufficient to more than offset the costs of the chemical, and the additional steps involved in its use, is a practical matter that must be determined by the user for his particular soil and cropping system.

Nitrification – essential or non-essential?

Could there be a normal agriculture with abundant crop yields year after year if there were no nitrifying microorganisms in the soil? We cannot answer this question now with complete confidence, for the nitrifying microorganisms are everywhere. Any partial answer must be based largely on numerous solution culture experiments with various plant species, on vegetative experiments in the greenhouse, and on soil studies in the laboratory. The question is introduced into the present discussion only because the objectionable aspects of nitrification are being increasingly emphasized.

What are the reported bad effects of nitrification? The more important are: (1) the greatly increased leachability of nitrites and nitrates in comparison with ammonia; (2) the instability and reactivity of nitrites which may lead to volatile losses of nitrogen; (3) the increase in soil acidity as a result of nitrate formation, especially where the nitrates are lost by leaching. With increase in acidity there may be toxic effects on plants produced by nitrites and aluminum and also excessive loss of mineral elements.

The ability of many kinds of plants to make a normal growth under controlled conditions with ammonia as the sole source of nitrogen has been shown repeatedly. It has also been shown that many plants prefer nitrate (Tiedjens and Robbins, 1931) and can often thrive on it under conditions where ammonia is a poor source of nitrogen. This is likely to be the case in strongly acid soils. It is also true that when plants are forced to live wholly on ammonium ions they will often substitute these ions for Ca, Mg, and K, thereby causing an imbalance of minerals in the plant. Plants normally have a cation–anion balance that is characteristic of the genus. Legumes, for example, are known as base-loving, whereas grasses have lower base requirements. When a plant assimilates basic ammonium ions that are converted into protein in the plant the ash may then show cation deficiency. In extreme cases growth may be greatly curtailed and abnormal. These bad effects tend to increase in magnitude as the soil pH is lowered.

The most logical, but tentative answer to the question raised above is that we could probably get along satisfactorily without soil nitrifying bacteria if, and only if, much of our fertilizer nitrogen were applied as nitrate, and if lime were applied abundantly to maintain a pH of perhaps 6 or above. In soils that receive no nitrogen fertilizers, or nitrogen only in the ammonia form, problems could be expected with some or most of our crops. After all factors are considered, it is the author's opinion that it is fortunate that the nitrifiers are everywhere. Any extra loss of nitrogen, for which they may be responsible, is more than compensated for by the better nutrient conditions that they help to bring about.

REFERENCES

Aleem, M.I.H., Engel, M.S. and Alexander, M., 1957. *Bact. Proc., Soc. Am. Bacteriol.*, 9.

Aleem, M.I.H. and Alexander, M., 1958. *J. Bacteriol.*, 76: 510–514.

Aleem, M.I.H. and Alexander, M., 1960. *Appl. Microbiol.*, 8: 80–84.

Aleem, M.I.H. and Nason, A., 1959. *Biochem. Biophys. Res. Commun.*, 1: 323–327.

Alexander, M., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 307–343.

Alexander, M., Marshall, K.C. and Hirsch, P., 1960. *Trans. Int. Congr. Soil Sci., 7th, Madison, Wisc., 1960*, 2: 586–591.

Allison, F.E., 1931. *J. Am. Soc. Agron.*, 23: 878–908.

Allison, F.E. and Doetsch, J., 1951. *Soil Sci. Soc. Am., Proc.*, 15: 163–166.

Allison, F.E. and Sterling, L.D., 1949. *Soil Sci.*, 67: 239–252.

Amer, F.M. and Bartholomew, W.V., 1951. *Soil Sci.*, 71: 215–219.

Brar, S.S. and Giddens, J., 1968. *Soil Sci. Soc. Am., Proc.*, 32: 821–823.

Bremner, J.M. and Nelson, D.W., 1968. *Trans. Int. Congr. Soil Sci., 9th, Adelaide, S.A., 1968*, 2: 495–503.

Broadbent, F.E., Tyler, K.B. and Hill, G.N., 1957. *Hilgardia*, 27: 247–269.

Doxtader, K.G. and Alexander, M. 1966. *Soil Sci. Soc. Am., Proc.*, 30: 351–355.

Edwards, A.P. and Bremner, J.M., 1966. *Rep. F.A.O.-I.A.E.A. Tech. Meet. – Use of Isotopes in Soil Organic Matter Studies.* Pergamon, New York, N.Y., pp. 347–348.

Engel, M.S. and Alexander, M., 1958. *Nature*, 181: 136.

Eylar Jr., O.R. and Schmidt, E.L., 1959. *J. Gen. Microbiol.*, 20: 473–481.

Fitts, J.W., Bartholomew, W.V. and Heidel, H., 1953. *Soil Sci. Soc. Am., Proc.*, 17: 119–122.

Fitts, J.W., Bartholomew, W.V. and Heidel, H., 1955. *Soil Sci. Soc. Am., Proc.*, 19: 69–73.

Fraps, G.S. and Sterges, A.J., 1930. *Tex. Agric. Exper. Stn. Bull.*, 412: 1–15.

Fraps, G.S. and Sterges, A.J., 1935. *Soil Sci.*, 39: 85–94.

Frederick, L.R., 1956. *Soil Sci. Soc. Am. Proc.*, 20: 496–500.

Führ, F. and Bremner, J.M., 1964a. *Atompraxis*, 10: 109–113.

Führ, F. and Bremner, J.M., 1964b. *Landwirtsch. Forsch.*, 18: 43–51.

Goldberg, S.S. and Gainey, P.L., 1955. *Soil Sci.*, 80: 43–53.

Goring, C.A.I., 1962a. *Soil Sci.*, 93: 211–218.

Goring, C.A.I., 1962b. *Soil Sci.*, 93: 431–439.

Goring, C.A.I., and Clark F.E., 1948. *Soil Sci. Soc. Am., Proc.*, 13: 261–266.

Greenland, D.J., 1962. *J. Agric. Sci.*, 58: 227–231.

Hanway, J. and Dumenil, L., 1955. *Soil Sci. Soc. Am., Proc.*, 19: 77–80.

Harmsen, G.W. and Kolenbrander, G.J., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 43–92.

Harmsen, G.W. and Van Schreven, D.A., 1955. *Adv. Agron.*, 7: 299–398.

Hauck, R.D. and Stephenson, H.F., 1965. *J. Agric. Food Chem.*, 13: 486–492.

Hirsch, P., Overrein, L. and Alexander, M., 1961. *J. Bacteriol.*, 82: 442–448.

Keeney, D.R. and Bremner, J.M., 1966. *Agron. J.*, 58: 498–503.

Krase, H.J., 1932. In: H.A. Curtis (Editor), *Fixed Nitrogen.* Chem. Pub. Co., New York, N.Y., pp. 366–408.

Lees, H. and Quastel, J.H., 1946. *Biochem. J.*, 40: 815–823.

Meiklejohn, J., 1951. *Plant Soil*, 3: 88–93.

Meiklejohn, J., 1953. *J. Soil Sci.*, 4: 59–68.

Molina, J.A.E. and Rovira, A.D., 1964. *Can. J. Microbiol.*, 10: 249–257.

Mortland, M.M., 1958. *Adv. Agron.*, 10: 325–348.

Mortland, M.M., 1965. *Soil Sci. Soc. Am., Proc.*, 29: 514–519.

Mortland, M.M. and Wolcott, A.R., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 150–197.

Nason, A., 1962. *Bacteriol. Rev.*, 26: 16–41.

Reuss, J.O. and Smith, R.L., 1965. *Soil Sci. Soc. Am., Proc.*, 29: 267–270.

Richard, T.A., Attoe, O.J., Moskal, S. and Truog, E., 1960. *Trans. Int. Congr. Soil. Sci., 7th, Madison, Wisc, 1960, Comm.*, II: 28–35.

Robinson, J.B.D., 1968. *J. Soil Sci.*, 19: 269–290.

Rubins, E.J. and Bear, F.E., 1942. *Soil Sci.*, 54: 411–423.

Russell, E.W., 1961. *Soil Conditions and Plant Growth.* Longmans Green, London, 9th ed., 688 pp.

Schloesing, T. and Müntz, A., 1877. *C. R. Acad. Sci.*, 84: 301–303; 85: 1018–1020; 86: 892–895.

Schmidt E.L., 1954. *Science*, 119: 187–189.

Schmidt, E.L., 1960. *Trans. Int. Congr. Soil Sci., 7th, Madison, Wisc., 1960*, 2: 600–607.

Sims, J.L. and Blackmon, B.G., 1967. *Soil Sci. Soc. Am., Proc.*, 31: 676–680.

Sims, J.L., Wells, J.P. and Tackett, D.J., 1967. *Soil Sci. Soc. Am., Proc.*, 31: 672–675.

Smith, D.H. and Clark, F.E., 1960. *Soil Sci.*, 90: 86–92.

Smith, J.H., 1964. *Soil Sci. Soc. Am., Proc.*, 28: 640–644.

Soulides, D.A. and Clark, F.E., 1958. *Soil Sci. Soc. Am., Proc.*, 22: 308–311.

Stanford, G., 1968a. *Soil Sci.*, 106: 345–351.

Stanford, G., 1968b. *Soil Sci. Soc. Am., Proc.*, 32: 679–686.

Stanford, G., 1969. *Soil Sci.*, 107: 323–328.

Stanford, G. and DeMar, W.H., 1969. *Soil Sci.*, 107: 203–205.

Stanford, G. and DeMar, W.H., 1970. *Soil Sci.*, 109(3): 190–196.

Stanford, G. and Hanway, J., 1955. *Soil Sci. Soc. Am., Proc.*, 19: 74–77.

Stanford, G. and Legg, J.O., 1968. *Soil Sci.*, 105: 320–326.

Stanford, G., Legg, J.O. and Chichester, F.W., 1970. *Plant Soil*, 33: 425–435.

Stevenson, F.J., Harrison, R.M., Wetselaar, R. and Leeper, R.A., 1970. *Soil Sci. Soc. Am., Proc.*, 34: 430–435.

Stevenson, F.J. and Swaby, R.J., 1964. *Soil Sci. Soc. Am., Proc.*, 28: 773–778.

Taber, S., 1942. *Science*, 96: 535–536.

Tiedjens, V.A. and Robbins, W.R., 1931. *N. J. Agric. Exper. Stn. Bull.*, 526: 1–46.

Theron, J.J., 1951. *J. Agr. Sci.*, 41: 289–296.

Tyler, K.B., Broadbent, F.E. and Hill, G.N. 1959. *Soil Sci.*, 87: 123–129.

Tyler, K.B., and Broadbent, F.E., 1960. *Soil Sci. Soc. Am., Proc.*, 24: 279–282.

Waksman, S.A., 1932. *Principles of Soil Microbiology.* Williams and Wilkins, Baltimore, Md., 2nd ed., 894 pp.

Waksman, S.A., Madhok, M.R. and Hollaender, A., 1937. *Soil Sci.*, 44: 441–446.

Waksman, S.A., 1952. *Soil Microbiology.* Wiley, New York, N.Y., 356 pp.

Waksman, S.A. and Madhok, M.R., 1937. *Soil Sci.*, 44: 361–375.

Winogradsky, S., 1890. *Ann. Inst. Pasteur*, 4: 213–231; 257–275; 760–771.

Winogradsky, S. and Omeliansky, W., 1899. *Zentralbl. Bakteriol.*, II, 5: 329–343: 377–387; 429–440.

Chapter 13

LOSS OF NITROGEN FROM SOILS

INTRODUCTION

Nitrogen is the most important nutrient element in soil organic matter when considered from the economic standpoint. Carbon is also equally essential for crop production but it is available in the atmosphere at no cost to the tiller of the soil. Under many conditions it has been repeatedly shown that the benefits derived from the addition of plant and animal residues to soil, as well as from the native soil organic matter, may be attributed almost wholly to the available nitrogen derived from these sources of organic matter. In other words, crop yields often parallel the quantities of nitrogen released from organic matter. This does not mean that other nutrients present in soil organic matter and discussed in a later chapter are not important but rather that nitrogen is needed in larger amounts than are the other mineral elements and is likely to be more deficient if crop yields are maintained at a comparatively high level.

Nitrogen is also the most transient element, other than carbon, that is present in organic matter. It was pointed out in a preceding chapter that when plant and animal residues are added to a soil under conditions favorable for microbial activity, decomposition normally proceeds at a very rapid rate. These residues serve as readily available sources of energy for microorganisms, and energy supply is the determining factor in the growth of most soil-inhabiting microorganisms. They get their energy in much the same manner that animals do by decomposing sugars, starches, fats and proteins. Soil organisms decompose almost all of the organic substances present, including cellulose, hemicellulose and even lignin at a slow rate.

In the process of decomposing fresh organic matter sources it is common for perhaps 40–90% of the carbon in the decomposed portions of these substances to be liberated as carbon dioxide. Fungi usually release less of the carbon than do bacteria. This is because fungi often use up to 60% of the carbon in the construction of their own cell walls and protoplasm. Bacterial species vary widely in this respect but it seems that most of those active in soils retain only 10–25% of the carbon in their bodies. Of course, in all cases this retention is rather temporary because the life span of bacteria, fungi and actinomycetes is often only a few days. The dead cells are then subject to attack by other organisms, with accompanying loss of a portion of the microbial carbon.

Accompanying the release of carbon there also occurs a release of nitrogen as ammonia, as well as other mineral elements present. A portion of this ammonia may be immobilized biologically, may be sorbed by the organic and inorganic colloids present, or may be fixed chemically by the clays or organic matter present. However, the major portion of the nitrogen is normally oxidized to nitrites and nitrates. The various pro-

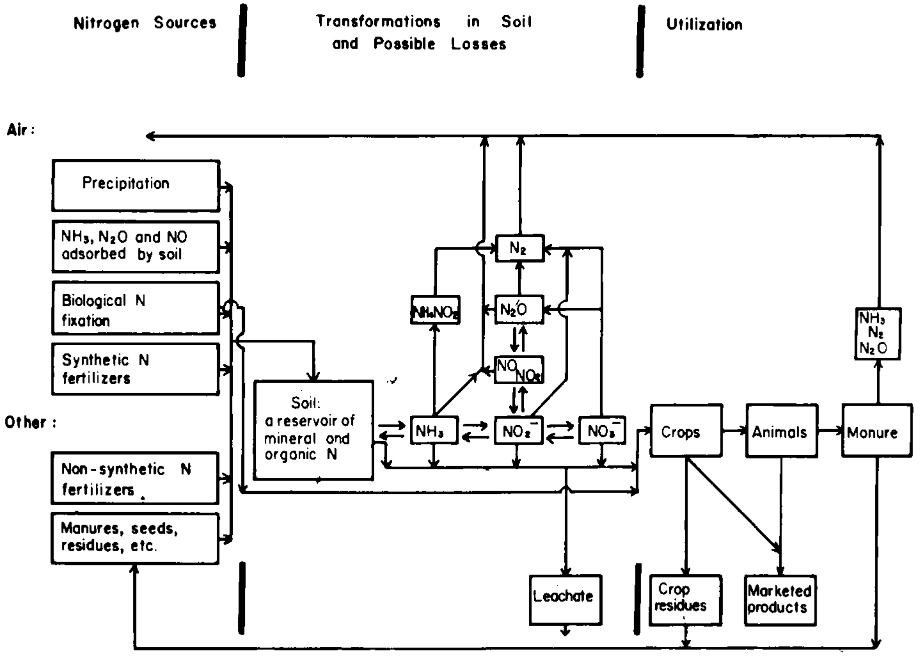

Fig.13.1. Soil nitrogen sources and transformations, and fate of end products. (From Allison, 1965.)

cesses, shown diagrammatically in Fig.13.1, involve a variety of enzymatic and chemical steps, including hydrolysis, oxidation, reduction, volatilization and direct chemical reactions with other soil constituents, and offer numerous opportunities for escape of nitrogen either to the drainage waters or to the air. In view of the fact that the obtaining of maximum benefits from organic matter management is so dependent upon what happens to nitrogen it seems advisable to outline some of the channels by which nitrogen may be lost from the soil. Some of the practical means of reducing these losses are presented in a later chapter.

SOIL NITROGEN VS FERTILIZER NITROGEN

When the efficiency of utilization of nitrogen by crops is under discussion the reference is usually to the effectiveness with which fertilizer nitrogen is taken up by crops. However, no distinction should be made between the nitrogen derived from fertilizers and that derived from soil organic matter and crop and animal residues, because the forms in which plants assimilate nitrogen are, with only slight exceptions, the same regardless of their original source. Plants assimilate almost all of their nitrogen in the forms of inorganic nitrogen, chiefly ammonia and nitrates, with traces of nitrites. A few simple forms of organic nitrogen, such as amino acids and urea, can be utilized directly by plants but such forms are normally present in such small amounts, and are so transitory, that they can be largely ignored in a consideration of the fate of available nitrogen in soils.

The chief difference between soil organic matter nitrogen and fertilizer nitrogen that sometimes requires consideration is that of quantity likely to be present at any given time. Ninety-five percent or more of the nitrogen present in fertile topsoil is usually present in the organic form which, as already pointed out, is released only slowly during a growing season. The total released during a whole year may be only 25 to 100 lb. per acre. In contrast, it is not unusual for much larger amounts of nitrogen to be applied in a single application to a corn crop where the chief nitrogen source is commercial nitrogen. Most of this nitrogen is usually in the forms of ammonia, nitrate, or urea that is quickly converted into ammonia in the soil. The addition of so much available nitrogen that cannot be utilized immediately by the crop sometimes favors nitrogen losses, both in the drainage water and as gases. Some of the conditions under which this can occur are discussed below.

RECOVERY OF NITROGEN BY CROPS

Non-tracer experiments

Many experiments have been reported showing the recovery of nitrogen added as fertilizer or released from soil organic matter. In all experiments conducted prior to 1950 and some since then, recovery of nitrogen was commonly determined by growing crops on fertilized and unfertilized soil and subtracting the nitrogen content of the latter from that of the former. The experiment may either have been continued for many years with yearly applications of nitrogen, or it may have been for a single fertilized crop with or without a second unfertilized crop grown to recover residual nitrogen. About 1950 the heavy nitrogen technique was introduced; since that time most nitrogen recoveries have been determined by this ^{15}N-technique, and are more accurate although largely limited to greenhouse tests because of the cost of the heavy nitrogen.

Many of the earlier experiments conducted in lysimeters, buried cylinders, and in the greenhouse are reviewed by Allison (1955). The lysimeter experiments show that the recoveries of nitrogen by crops grown over a period of years amounted to only 40–75% of the nitrogen that was added or made available from the soil. Low recoveries were usually obtained where the nitrogen additions were so large that all of it was not used promptly, where the soil was very sandy, or where the crop made a slow and limited growth. Most lysimeters are filled with soil to a depth of 4 ft. or less, and many of them contain only 18–24 inches of soil. Hence, a considerable portion of the unrecovered nitrogen is often found in the leachates. It is noteworthy that the recoveries of nitrogen in the lysimeter experiments, discussed by Allison, were not appreciably different whether the nitrogen was supplied as ammonia, nitrate, or organic nitrogen. This is not surprising since conditions in most lysimeters are favorable for rapid nitrification, and undoubtedly the bulk of the nitrogen was absorbed by plants as nitrate regardless of the form in which it was supplied.

A very interesting experiment is the 40-year cylinder experiment conducted at New Brunswick, New Jersey, and reported by Prince et al. (1941). This experiment resembled lysimeter experiments except that there was no provision for collecting the leachates. After removing the soil and putting the cylinders in place, the subsoil was replaced and an 8-inch layer of Penn loam was added. Where lime was added the percent nitrogen recoveries in the crops of the added nitrogen and that made available from the soil were as follows: manure 46, ammonium sulfate 53, dried blood 55, and sodium nitrate 54; in the absence of lime the percent recoveries in the same order were 39, 22, 27, and 32. The extreme effect of acidity on nitrogen recovery is emphasized by these data.

Open field experiments were also conducted at the New Jersey Experiment Station by Lipman et al. (1928) during the period 1908 to 1927. The percent nitrogen recoveries for the 20-year period from limed soils were: calcium nitrate 42, ammonium sulfate 42, calcium cyanamide 36, sodium nitrate 33, fish scrap 26, tankage 26, and manure 12. On the unlimed soils the recoveries in the same order were 32, 21, 33, 37, 37, 21, and 17%.

Field experiments conducted at Rothamsted, England (Russell, 1950) show recoveries in the crop of about 50% of the nitrogen added as ammonium sulfate and 30% of that added as farm manure. Most of the remainder was apparently lost in the drainage waters.

Pearson et al. (1961) reported the results of short-time experiments conducted in the southeastern part of the United States during the period 1956 to 1959. The nitrogen sources were ammonium nitrate, ammonium sulfate, anhydrous ammonia, sodium nitrate and urea. The average recoveries of nitrogen in the first crop grown on several soils were 40–60% of that applied in the spring. Two additional unfertilized crops brought the recovery values to 70–77%. Evidently the first crop did not assimilate all of the nitrogen that was available to it and the residual crops utilized much of it before it could escape in the drainage waters. The recovery of nitrogen applied in the fall, and the soil left uncropped until the spring, was only 62% as high as for spring-applied nitrogen.

The recovery of nitrogen applied to grasses is normally much higher than when applied to cultivated crops because the grasses assimilate it rapidly and there is practically no leaching of nitrogen from a soil covered with a dense sod. This is illustrated very vividly by the results of Ashley et al. (1965). They applied ammonium nitrate in five split applications at rates of 300–600 lb. of nitrogen per acre per year for 5 years to Coastal bermudagrass. Either two or three residual crops followed. The recovery of applied nitrogen was approximately 88 and 76% for the low and high rates, respectively. Corresponding values for Pensacola bahiagrass were 72 and 70%.

The experiment of Boawn et al. (1960) is of unusual interest because it was conducted under irrigated conditions in a dry-land region where there was no leaching. Ammonium sulfate, ammonium nitrate, and calcium nitrate were applied at rates of 40 to 160 lb. per acre annually for four years and then two unfertilized crops followed. The nitrogen recoveries for the three nitrogen sources in the order mentioned were 88, 86 and 83%.

Many other experiments similar to those mentioned above have been reported from all over the world, but the ones discussed are typical and representative. It will be noted that recoveries from the earlier experiments were commonly much lower than from those conducted more recently. This is partly because of the lower rates of nitrogen used in these earlier experiments, which increases the difficulty in measuring recovery accurately. Furthermore, the use of greatly improved experimental techniques in later years has proved beneficial and led to more accurate measurements of nitrogen recoveries. Later experiments have usually been more carefully planned to get good recoveries by avoiding experimental conditions that were known not to represent the best-known farm practices.

Tracer experiments

In tracer experiments the form of nitrogen to be studied is tagged by substitution of a few percent of ^{15}N-nitrogen for the ^{14}N-nitrogen present in the commercial form of nitrogen. The percentage substitution may be between about 2 and 100% but is usually in the order of 5 to 10% in most vegetative tests, but this depends upon the type of experiment and the accuracy of measurement desired. Most tracer experiments, as already stated, have been conducted in the greenhouse and results are reported in terms of nitrogen recovered in the crop plus that left as unavailable (immobilized) nitrogen in the soil. When this tracer procedure is used it is absolutely necessary to analyze the soil for residual ^{15}N-nitrogen because accuracy is dependent upon accounting for all of the added tracer not lost as gases.

A summary of some of the more important and representative greenhouse experiments conducted for the purpose of determining the fate of tagged nitrogen added to soils is given in Table 13.I. The recoveries of added nitrogen in the crop and soil were in the range of 53–100%, and averaged about 82%. Only rarely was all of the nitrogen accounted for, and the mechanisms of loss are unknown, but many of the investigators mentioned denitrification as the most likely channel of loss. A more detailed discussion of these experiments is given by Allison (1966).

The experiment of Dilz and Woldendorp (1960), not listed in Table 13.I, is of interest, because it was both a pot experiment and a field experiment. Pots containing grass sods were buried in the open, tagged potassium nitrate was added, and three cuttings of grass were made during the following 70 days. The recoveries of nitrogen in the harvested crop, roots and soil were 78% for a clay soil and 84% for a sandy soil; for a peat maintained at 95% and 80% of its water-holding capacity the recoveries were 60% and 81%, respectively. According to the authors, these values may be slightly low because no provision was made for the inclusion of nitrates in the analyses. Presumably the losses were due chiefly to denitrification.

In a greenhouse study, conducted by Simpson and Freney (1967), labelled ammonium and nitrate nitrogen were added separately to three Australian soils of different organic matter contents. After 6 weeks and again after 35 weeks the fate of the ^{15}N was determined in the presence and absence of ryegrass plants. Ninety to 100% of the ^{15}N-N was recovered in the soil–plant system from the two soils of lowest nitrogen content, but only 69% from the high-N soil. Ammonium was immobilized more rapidly than nitrate, particularly in the low-N soil, which led to a greater uptake of nitrate-N than of NH_4-N

TABLE 13.I

RECOVERIES OF NITROGEN (CROP PLUS SOIL) IN GREENHOUSE EXPERIMENTS USING ^{15}N-TAGGED NITROGEN SOURCES* (from ALLISON, 1966)

Investigator	*N source*	*N recovery (%)*
MacVicar et al. (1951)	$(NH_4)_2SO_4$	85–97
Wallace and Smith (1954)	Avocado leaves	94–100
	Orange leaves	60–96
	Orange roots	84–87
Walker et al. (1956)	$(NH_4)_2SO_4$	70–75
	KNO_3	66–71
Tyler and Broadbent (1958)	$(NH_4)_2SO_4$	95–98
	NH_4NO_3	88–94
	NH_4OH	81–84
Legg and Allison (1959)	$(NH_4)_2SO_4$	90–100
	$NaNO_3$	91–98
Cady and Bartholomew (1960b)	$(NH_4)_2SO_4$	74–83
Turtschin et al. (1960)	$(NH_4)_2SO_4$	66–89
Legg (1962)	$NaNO_3$	90
Broadbent and Tyler (1962)	$(NH_4)_2SO_4$ (cropped)	68–80
	$(NH_4)_2SO_4$ (uncropped)	56–72
	KNO_3 (cropped)	65–79
	KNO_3 (uncropped)	53–62
Martin et al. (1963)	NH_4NO_3	94
Jansson (1963)	$(NH_4)_2SO_4$	90–92
	$NaNO_3$	86–90
Dinchev (1964)	$(NH_4)_2SO_4$	72–81
Broadbent and Nakashima (1965)	$(NH_4)_2SO_4$	61–79
Broadbent and Nakashima (1967)	KNO_3 (cropped)	95–98
	KNO_3 (uncropped)	78–89

*References here not quoted in the reference list can be found in Allison (1966).

by the ryegrass. The total labelled plus indigenous mineral N in unplanted soils, and the N taken up by plants, were similar for the two forms of added N. The highest apparent fertilizer efficiency of the added N (increase in total N uptake by the plants) occurred in the low-N soil. The highest recovery of ^{15}N-N by plants (80%) was realized where nitrate was added to the two soils of lowest N content.

In lysimeter experiments where urea-^{15}N was added to raw humus in a boreal forest soil, Overrein (1968) observed no losses of nitrogen oxides during a 12-week period where N was added at rates from 100 to 1000 kg N/ha. At the highest rate of addition, 3.5% of the added N was lost as ammonia, but only traces of tagged N_2 escaped to the atmosphere.

In another similar lysimeter experiment Overrein (1969) added tagged urea, ammonium chloride and potassium nitrate to a podzolic forest soil at rates of 0, 10, 25, 50 and 100 g N/m^2. Ammonia volatilization occurred only where urea was added and even then amounted to a maximum of 3.5% of the added N. Trace amounts of isotopic N_2 were found at the heaviest urea application only. Nitrogen oxides were never detected in the atmosphere above the lysimeters regardless of source of N added.

Two unique field experiments were reported by Carter et al. (1967) in which both tagged $(NH_4)_2SO_4$ and $NaNO_3$ were used. These experiments were conducted at Thorsby, Alabama, on a fine sandy loam. Iron cylinders, either one or two feet in diameter, were pressed into the soil to a depth of 18 or 24 inches. The soil inside these cylinders constituted a plot and was fertilized at the rate of 250 lb. of nitrogen per acre. Provision was made for covering the plots as desired with clear plastic for brief periods when it seemed likely that heavy rains might occur. Irrigation water in small amounts was added as necessary. The soil in some cylinders was left uncropped and in others sudangrass was planted. The grass was harvested at the early seeding stage, and the tops, roots and soil by 6-inch layers, were analyzed for total and excess ^{15}N-N. The recoveries of nitrogen from 32 cylinders averaged 99% and ranged between 96 and 102% for the various treatments. Even four plots that were not covered with plastic at any time showed nitrogen recoveries of the same magnitude.

A second experiment at the same location by Carter et al. (1967), using the same techniques, was conducted the following year. The recoveries of nitrogen after 8 weeks ranged between 88 and 96%, being slightly higher where cropped than uncropped, and also slightly higher with $(NH_4)_2SO_4$ than with $NaNO_3$. Neither fertilizer concentration, soil pH, nor the presence of an inhibitor of nitrification appreciably affected the recovery of ^{15}N-N. Where the plots were left uncovered the rainfall carried some of the nitrogen beyond the root zone and sampling level and the recoveries of nitrogen were only 71% for $NaNO_3$ and 83% for $(NH_4)_2SO_4$. The authors were of the opinion that denitrification was responsible for most of the losses from the cylinders where protected from heavy rainfall. There is no apparent satisfactory reason for the lower over-all recoveries in the second season than in the first.

LOSS BY EROSION

When the channels by which nitrogen is lost from soils are under discussion the matter of losses by erosion is commonly not mentioned. This is not because of failure to recognize the importance of this source of loss but rather because there are few data that show accurately the magnitude of this factor, and also because nearly all experiments designed to measure nitrogen recovery are conducted either in the greenhouse, in lysimeters, or on level areas of field soils where erosion does not occur.

Lipman and Conybeare (1936) estimated that erosion removes an average of 24.2 lb. per acre of nitrogen annually from arable soils in the United States. Since soils vary so widely in nitrogen content, in agricultural treatment, and in erodibility, it is obvious that there is a very wide variation in losses from this average value of 24.2 lb.; the loss may be zero on many soils and amount to 100 or more lb. of nitrogen on others. Factors that affect the losses are discussed at considerable length by Bennett and Lowdermilk (1938) and by Stallings (1957). Erosion losses now may be less than the estimate made by Lipman and Conybeare for the reason that their estimate was based on farm practices prior to 1936 when erosion was very inadequately controlled. The higher rates of nitrogen now used may, however, work in the opposite direction. Tremendous efforts toward controlling erosion have been made during the past 30 years and farming is now on a far more scientific basis than in the earlier years. Nitrogen is especially subject to loss via water movement because the water loosens the organic matter, which may then float away. Massey and Jackson (1952) observed that the eroded material from Wisconsin plots contained 2.7 times as much nitrogen as the soil proper; Neal (1944) states that values as high as 5-fold are encountered. Wind, likewise, removes the lightest materials first. Stoltenberg and White (1953) also state that "erosion was found to be a selective process such that the eroded material contained considerably more plant nutrients than the soil from which it was eroded. This selective process resulted in a decrease in soil fertility, a decrease in organic matter, and changes in texture" (see Chapter 27).

Even though erosion may only move the nitrogen from one part of the field to another, this may affect average productivity on a given farm almost as much as if removed completely, because the nitrogen is deposited in places and at depths such that it is far less valuable than it was in its original location. It scarcely need be added that the many other harmful effects of erosion often far outweigh nitrogen loss.

Nitrogen losses of fertilizer nitrogen in surface runoff, following its application to the surface of soils, are likely to be less than one might expect. For example, tests made by the U.S. Department of Agriculture and the Tennessee Valley Authority showed that when granular ammonium nitrate was added to the surface of a sandy loam of 5% slope the runoff losses of nitrogen produced by 5 inches of rainfall during a 2-hour period were only 2.3% from a fallow soil and 0.15% from a sod. At more nearly normal rainfall rates, runoff losses under such conditions would doubtless be too small to be of practical importance.

LOSS THROUGH LEACHING

Leaching is commonly the most important channel of unaccounted-for loss of nitrogen from field soils. The loss occurs almost wholly as nitrate, the movement of which is closely related to water movement. Wetselaar (1962), for example, observed a positive correlation of 0.946 between nitrate movement and rainfall. Gardner (1965a) has presented an excellent theoretical discussion of the movement of water, and of nitrates dissolved in it, and hence this phase of the subject will be discussed here only briefly.

Allison (1965) lists the more important variables that determine nitrogen loss. These are: (1) form and amount of soluble, unabsorbed, nitrogen present; (2) amount and time of rainfall; (3) infiltration and percolation rates; (4) water-holding capacity of the soil and its moisture content at the time of rainfall; (5) vegetative cover; (6) evapotranspiration; (7) nitrogen uptake by the crop; (8) extent of upward movement of nitrogen during droughts; (9) and whether the nitrogen is leached below the root zone. Burns and Dean (1964) mention two other factors that affect movement of nitrate in soils, namely the cation associated with the nitrate, and the temperature.

Wetselaar (1962; also see Gardner, 1965a,b) has shown that nitrate is gradually diluted out of the topsoil and it may accumulate, at least temporarily, at depths of one or more feet unless the rain is sufficiently heavy to carry it beyond the root zone or to the ground waters. Shaw (1962) states that heavy and continuous rain is required to remove nitrates completely from either light or heavy soils, and there is little difference in the amount of rain required to remove nitrate from the surface layers of the two types of soil. Burns and Dean (1964) made a study of the movement of nitrate from band applications and concluded that under certain conditions much of the nitrate can move downward from a band very rapidly, or in their words "drop out", when the moisture is above field capacity.

Nitrates can also move upward during very dry periods (Krantz et al., 1944) and is evidenced by crust formation at the surface where the soluble salts sometimes accumulate in quantity. The data of Wetselaar (1962) would seem to indicate that this reverse movement of nitrates is largely confined to the upper 18 inches of soil. This would of course depend on many factors, including soil texture, structure and length of the dry period.

There are few data that show accurately the amount of nitrogen that leaches through soils under field conditions. Most of the data that are available have necessarily been obtained from lysimeters. These are of two kinds, the filled-in and the monolith types. In the filled-in type the soil is removed from the field, thoroughly mixed by horizons, and placed in tanks in the natural order. The tanks commonly vary from 1 to 5 ft. in diameter and may be 1.5 to 6 ft. in depth. In the other less common monolith lysimeter the soil profile is left undisturbed and is surrounded by a metal or concrete wall. The soil may be removed intact from its original location, or it may merely be surrounded by a wall and left in place. In both types of lysimeters the percolation is collected and analyzed at frequent intervals. The lysimeter method is obviously an artificial system that has been subject to many criticisms. Nevertheless, it has furnished much valuable information, especially on the effect of comparative treatments, but seldom can the data be considered in a quantitative way as a measure of what is happening under field conditions. Since Allison (1955, 1965) has summarized the results obtained in several lysimeter experiments, the subject need not be considered further in the present discussion.

Precipitation–evaporation data are now being used as an indirect way of evaluating the extent to which nitrogen is likely to be lost from any given soil at any given time under average rainfall and climatic conditions for the region. It gives only a qualitative picture but does furnish valuable practical information that enables the farmer to plan his cropping and fertilization system so as to minimize nitrogen losses in the drainage waters.

The customary way of making use of precipitation–evapotranspiration data is that followed by Van Bavel of the United States Department of Agriculture and members of the staffs of various state experiment stations. They have made continuous yearly plots by months of evapotranspiration losses superimposed upon plots of precipitation, or preferably infiltration, data. The precipitation data used are usually calculated from the daily rainfall records of the U.S. Weather Bureau for the past 25 years. The evapotranspiration values are based on known radiation and experimental data that show the probable losses of moisture under average conditions of soil, crop and climate at any given location. Such graphs show if percolation is likely to occur and, if so, at what periods of the year. Whenever evapotranspiration losses exceed precipitation during a period of a few days there can obviously be no leaching unless the soil water exceeded field capacity initially. When precipitation, or infiltration, is greater than evapotranspiration, leaching may or may not occur depending upon the amount of water required to bring the soil to field capacity.

Graphs of typical precipitation–evapotranspiration data are shown in Fig.13.2 and 13.3. Fig.13.2* is the graph for Montgomery, Ala., prepared by Ward et al. (1959). Fig.13.3 is the graph for Raleigh, North Carolina, prepared by Van Bavel and Verlinden (1956). The annual rainfall at Montgomery and Raleigh are approximately 51 and 46 inches, repectively.

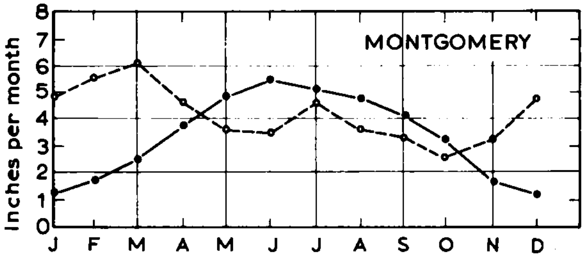

Fig.13.2. Monthly precipitation (P, dotted line) and monthly evapotranspiration (E, solid line) at Montgomery, Alabama. (Redrawn from Ward et al., 1959.)

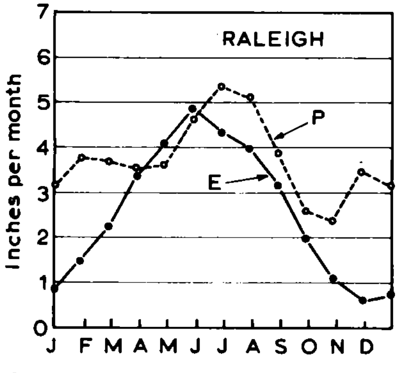

Fig.13.3 Average monthly precipitation and evapotranspiration at Raleigh, North Carolina. (Redrawn from Van Bavel and Verlinden, 1956.)

At Montgomery, as Fig.13.2 shows, during the period of approximately April 15 to October 15 evapotranspiration exceeded average precipitation, and hence loss of water with dissolved nitrates would normally be negligible during this 6-month period. It must be borne in mind, however, that these are average values. During infrequent periods when the rainfall amounts to several inches during a period of two weeks to a month some percolation to the subsoil could occur and of course nitrates would be carried along in the water. These graphs are also based on the water-holding capacity of medium-textured soils. Some leaching through a very sandy soil could be expected at times even when Fig.13.2 might indicate otherwise. During the period of late fall until April, rainfall greatly exceeds evapotranspiration at Montgomery and it is during this period that large losses of nitrogen in the drainage waters could be expected if nitrates accumulate, or are added, and there is no green crop present to assimilate them.

At Raleigh, as Fig.13.3 shows, the rainfall pattern is very different from that at Montgomery, a bigger percentage of the precipitation occurring during the summer months. Only during April and May does evapotranspiration exceed precipitation, and then by less than an inch of water per month. Under these conditions some leaching might be expected during most of the year, but even at Raleigh most of the water movement through the soil would be during the late fall and winter months.

Precipitation–evapotranspiration graphs for numerous other locations in the eastern states and a few for the midwestern region have been drawn. Reference will be made to the ones for Jackson, Miss. (Van Bavel, 1959), Richmond, Va. (Van Bavel and Lillard, 1957) and Minneapolis, Minn. (Blake et al., 1960). The graphs (not shown here) for these three locations are reproduced by Allison (1965). The annual rainfall for these in the order mentioned are 52, 43 and 28 inches. The rainfall–evapotranspiration pattern at Jackson resembles fairly closely that at Montgomery, as would be expected. The graph for Richmond resembles somewhat that for Raleigh but at Richmond there is less chance of leaching during the period of May 1 to October 1. At Minneapolis, where the rainfall is only 28 inches, the graph indicates no leaching during the summer months and none can occur during the remainder of the year because the soils are frozen. In the dryland regions farther west the rainfall seldom, if ever, penetrates beyond the root zone, and hence loss of nitrate nitrogen by leaching cannot occur.

These studies demonstrate very strikingly the need for caution in the management of cropping systems so as to avoid the accumulation of nitrates during the late summer months when conditions are commonly very favorable for the decomposition of soil organic matter, followed by rapid nitrification. This often occurs just at the time when the crop is maturing and has little need for available nitrogen. The graphs indicate that in the warm humid region much of this nitrogen will be lost to the drainage waters during the winter months unless a green crop is present to assimilate it. The experiments of Pearson et al. (1961), in which nitrogen fertilizers applied in the fall gave much lower recoveries of nitrogen than when applied in the spring, illustrate what can happen.

LOSS TO THE AIR AS AMMONIA

Ammonia is the primary identifiable nitrogenous product of the decomposition of soil organic matter and organic residues, and is constantly being formed at widely varying rates depending on the resistance of the organic sources to biological attack, and also on climatic and soil factors that determine the rate at which soil microorganisms can grow. In addition, large quantities of nitrogen are being added to soils as fertilizers, which may be in the form of ammonium salts, solutions, or gases. In the present discussion the term ammonia will be used to refer more or less interchangeably to ammonia and to ammonium ion. The two are not the same, of course, but since unionized ammonia may become ionized quickly, or vice versa, when added to soils, it is not feasible in this short discussion to try to differentiate between the two. Generally speaking, at low soil pH values the ammonia exists chiefly as ammonium ion and at high pH values and high concentrations it exists largely as free ammonia. It is as free unionized ammonia that escape to the atmosphere in gaseous form may occur. In considering the fate of ammonia in soils, the source can, for all practical purposes, be ignored after it is incorporated in the soil. The anion, if any, to which the ammonium ion is attached may have some effect but not much after equilibration with the soil.

When ammonia is formed in soil or is added several things can happen to it depending chiefly on the clay and organic matter content of the soil, the pH and moisture content, temperature, and the quantity of ammonia present. As Mortland (1958) says: "It may be immediately chemically sorbed by the clay minerals or organic matter. It may be physically sorbed by the colloidal complex or dissolved in the soil moisture. From these temporary repositories it may be eventually chemically sorbed or in the absence of available chemically reactive sites, may eventually diffuse through the soil pores to the surface and be lost to the atmosphere." He further points out that chemical sorption occurs to the greatest extent by clay minerals under acid conditions, and by organic matter under alkaline conditions. Physical sorption of ammonia does not require the presence of H ions, takes place at lower sorption energy than does chemical sorption, and is more easily reversible.

The primary concern in the present discussion is in the conditions that lead to volatilization of ammonia. In general, we may say that such losses may be expected when free ammonia is added in such amounts as to exceed the capacity of the soil to chemically sorb it; in other words, added after the reactive sites have been satisfied. The excess ammonia may not escape, at least immediately, because it is still weakly held by physical forces and by any moisture that may be present to dissolve it. It can also react with any acids present to form salts. Under like conditions volatilization can also occur if nitrogenous organic matter is being decomposed biologically in amounts exceeding the ability of the medium to absorb it. An illustration of this is the commonly observed strong odor of ammonia that is given off from a loose pile of lawn clippings during the early stages of decomposition. If the clippings are allowed to decompose in mixture with clay or a medium-textured soil no odor of ammonia is detected.

The increased attention that has been given in recent years to ammonia volatilization is due to the realization that such losses can be large under modern systems of farming unless adequate precautions are taken. This increased interest may be attributed to: (1) the higher rates of nitrogen now being used in comparison with those of a few years ago; (2) use of urea which is readily hydrolyzed to ammonia; and (3) extensive use of anhydrous ammonia and ammonia solutions. This subject is discussed by Allison (1966).

High rates of ammonia make complete retention in soils more difficult because of the danger of exceeding the ability of the soil to chemically sorb the ammonia, as already stated. This is especially true in soils of low exchange capacity, coarse texture, and high pH.

Much attention has also been given to the loss of ammonia following surface application of urea to sods and bare soils (Volk, 1959). Under such conditions the urea hydrolyzes to ammonia quickly and unless immediately washed into the soil the loss may amount to 10 to 30%. There is little or no loss if the urea is mixed with the soil. Moe (1967) found that losses of nitrogen through both leaching and volatilization could be minimized markedly by incorporation of urea with actively decomposing crop residues in the surface soil. Losses of nitrogen in surface runoff water, following surface application, are usually small and likely to be less from urea than from ammonium nitrate (Moe et al., 1967, 1968).

Much attention has been given to the best means of applying anhydrous or aqua ammonia and ammonia solutions, often at rates of 100 or more lb. of nitrogen per acre. The danger of loss here is on sandy soils with low exchange capacity, particularly at the higher rates. It is now established that under nearly all conditions, except possibly on the soils of very coarse texture, little ammonia is volatilized if it is properly added at a depth of not less than 4 inches.

Losses of ammonia derived from decomposing organic residues are usually negligible when they are incorporated in the soil. The losses can be high, however, when they decompose on the soil surface, and the higher the nitrogen percentage, and the more readily they decompose, the greater the loss. Negligible losses would be expected from decomposing straw, cornstalks and very strawy manures, but succulent legume and grass tops and chicken manure should liberate much ammonia if there is no absorbent present.

LOSS FROM GROWING PLANTS

Some nitrogen is lost from plants during their normal growth in the forms of pollen, dropped leaves, sloughed-off root cells and other non-seed tissues. Some of these plant parts may blow away but most of the nitrogen in them is returned to the soil. In the normal growth cycle of annual plants much of their total nitrogen needs are assimilated from the soil during the early growth period and, as growth proceeds, the nitrogen is constantly transferred from the older to the younger growing tissues. In the latter part of the growth cycle, when seed formation is in progress, a large portion of the nitrogen is laid down in these seeds. This seed nitrogen is of course not lost but is merely transferred to the next generation or removed in the harvest. The nitrogen in any nitrogen-deficient senescent leaves may be lost, however, as they fall during this period of approaching plant maturity.

Loss of nitrogen compounds from plants into soils is of common occurrence. Frank (1954) observed losses of 14 to 30% of the nitrogen from several plants during the last part of their growth period. Börner (1960) and Rovira (1962) in their reviews point out that plant-root exudates include a large number of nitrogenous compounds, particularly amino acids, that are exuded from young plants. The losses of root-cell and root-hair tissues increase with age of the plant, but such losses are common at other times if the conditions for growth become unfavorable.

Ammonia may occasionally be excreted in small amounts from the roots of many kinds of plants if nitrogen is relatively abundant and carbohydrate becomes deficient (Burstrom, 1945; McKee, 1949). Both ammonia and hydrocyanic acid have been demonstrated as minor products of seed germination and seedling growth.

Much work has been done during the past 50 years on the associative action of legumes and nonlegumes. Occasionally, but only occasionally, it has been demonstrated that a small portion of the nitrogen fixed from the air by legumes has been excreted and assimilated by the nonlegume growing in close association with it. Here, again, it seems that this excretion is associated with a low carbohydrate level in the legume plant (see discussion in Chapter 10).

Loss of molecular nitrogen from plants has long been recognized as a possibility (McKee, 1949) even though the quantity of loss is doubtless small. More recently Vanecko and Varner (1955) observed an evolution of small amounts of nitrogen gas when wheat containing nitrite was exposed to light. The usual explanation given for such observations is that the nitrogen is formed as a result of the interaction of the nitrite and plant amino acids. Absolute proof of this mechanism of loss is still lacking. There is no evidence at present to indicate that gaseous losses of nitrogen from soils via the plant are of appreciable practical importance.

LOSS VIA DENITRIFICATION

Denitrification is officially defined (see *Soil Sci. Soc. Am. Proc.*, 26: 307) as "the biological reduction of nitrate or nitrite to gaseous nitrogen (molecular nitrogen or the oxides of nitrogen)."

This mechanism of loss of nitrogen is now considered as one of the more important channels of loss from soils. As already pointed out, soil organic matter is constantly undergoing decomposition with the formation of ammonia as the end product of the degradation process. The ammonia rarely accumulates, however, for if not assimilated by plants or microorganisms it is oxidized rather rapidly to nitrite, and then to nitrate. In the absence of a crop, nitrate nitrogen may accumulate to the extent of 20, 50 or even 100 p.p.m. in fertile soils. Added fertilizer nitrogen, if not used by crops, likewise tends to accumulate as nitrate unless removed by leaching or by loss to the air in gaseous forms.

Denitrification to gaseous nitrogen is brought about by numerous species of bacteria that normally use oxygen from air as a hydrogen acceptor but under anaerobic conditions can substitute nitrates and nitrites for oxygen. Some of these facultative anaerobes can utilize both types of hydrogen acceptors simultaneously when molecular oxygen is very deficient (Allison, 1966).

Many experiments have been conducted over the years both in soils and in laboratory culture solutions that show that the ability to reduce nitrates and nitrites to nitrogen gas is a common characteristic of numerous species of bacteria that are universally present in soils and in decaying organic matter. Often the quantity of molecular nitrogen evolved represents 80% or more of that present in the original substrate; the unrecovered nitrogen is that which is converted into bacterial cells. By definition, it is obvious that biological denitrification can occur only where oxidized forms of nitrogen are present, and also only where there is a suitable source of energy present for the heterotrophic bacteria responsible for the reduction.

Fig.13.4 shows the rapidity with which nitrates can be reduced to nitrogen gas in soil maintained under completely anaerobic conditions. In these experiments, conducted by Jones (1951), 5 mg N in the form of potassium nitrate was added to an air-dry Codorus loam together with 0.5% sucrose and optimum moisture. It will be noted that nearly 50% of the nitrate was reduced to nitrogen gas within 2 days and about 80% within 3 days. If moist soil had been used rather than air-dry soil the rate would undoubtedly have been even more rapid. In similar experiments, where sucrose was omitted, the rate of nitrogen evolution was not appreciably different from that shown in Fig.13.4. The soil itself contained sufficient available energy material for a near-maximum rate of denitrification.

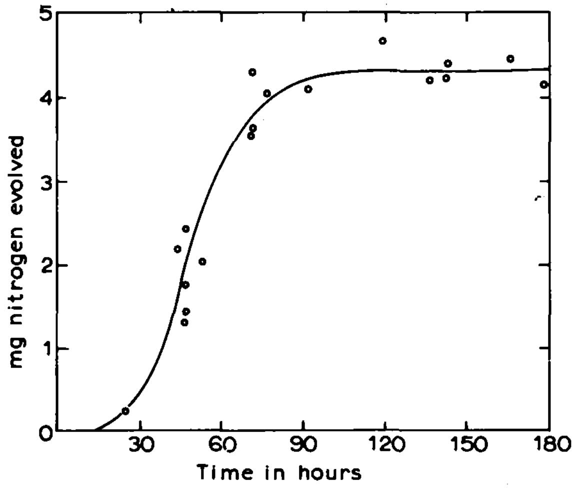

Fig. 13.4. Loss of nitrogen gas from nitrate in a soil maintained under anaerobic conditions. (From Jones, 1951.)

Tracer experiments showed that even in the presence of added ammonia the nitrogen gas was derived wholly from either added nitrate or nitrite nitrogen.

There is considerable uncertainty as to the fate of nitrate nitrogen, formed in the upper layers of soil, or added as fertilizer and not assimilated by crops. Does it move to the ground waters and escape in the drainage or is it largely reduced to nitrogen gas and lost to the air? Obviously, there is no single answer to this question. Such factors as soil texture, rainfall, organic matter content, aeration, ease of water penetration, nature of the subsoil materials, depth of soil, etc., determine the fate of the nitrogen. Meek et al. (1969, 1970) studied this problem under irrigation in California and reported that the nitrate concentration was high near the surface and decreased at depths approaching the water table, indicating nitrate reduction as the redox potential decreased. Only 1.5% of the 280 kg N per hectare applied to a cotton crop reached the tile drains during the growing season. These studies, together with other evidence, indicate that the danger of pollution of streams and lakes by nitrates leached from soils has been greatly overemphasized.

In the process of reduction of nitrates to nitrogen gas, nitrous oxide (N_2O) is a common intermediate (Wagner and Smith, 1958; Cady and Bartholomew, 1960a) and may be a necessary precursor of free nitrogen gas (Nõmmik, 1956). Some of it may escape from the soil before it is completely reduced. Arnold (1954) considered that it is likely that soils are an important source of N_2O found in the atmosphere.

The main facts that evolved from many researches conducted during the last part of the nineteenth century, and the early years of the present century, led to the generally accepted view at that time that denitrification is not an important factor in normal soils, except under special conditions. It was agreed, however, that if nitrate was present in soils that were not well-aerated due to causes such as poor structure, inadequate drainage, or periodic flooding for a few days, then much of the nitrate could be evolved as gas. It was generally concluded that the movement of air through most cultivated soils is so rapid that appreciable denitrification could not occur except during periods of heavy and continued rainfall. This view seemed to follow logically from gas analyses showing that the oxygen partial pressure in normal soils at plow depth is seldom more than 2 or 3% below that of air (20%), and, furthermore, laboratory experiments indicated that unless the partial pressure of oxygen in soils is reduced to levels much below this (perhaps to 2 to 5% or lower) denitrification is very limited or absent.

There was complete agreement among workers that loss of nitrogen by nitrate reduction could occur rapidly and often completely in loose piles of horse manure exposed to the air. Under such conditions the surface layer provides perfect conditions for rapid decomposition leading to ammonia formation, followed by rapid nitrification to nitrates. The nitrates would continue to accumulate in this outer layer for a time but would be leached downward by the first appreciable rainfall into the anaerobic portion of the manure pile. In this high energy and low oxygen environment there is a teeming population of bacteria that would be expected to utilize all of the transported nitrate within a period of a few hours. Nothing has happened in recent years to change this long-held view.

Recent data have thrown much doubt on the view that denitrification is not an important factor in most normal soils. This change in viewpoint may be attributed in part to the fact that the much larger applications of commercial nitrogen now being used, together with improved methods and more detailed knowledge of soil biochemistry and physics, have enabled us to understand better what is happening. We now know that denitrification is not limited to periods of excessive moisture but may occur in clay soils where the moisture content is below field capacity. Greenland (1962) observed that nitrification and denitrification can proceed simultaneously in some soils. The macropores in a soil may be well aerated, whereas the centers of the larger aggregates may be deficient in oxygen. This is because the diffusion of oxygen into these centers is not always rapid enough to replace the oxygen as fast as it is being utilized. There may also be pockets of decaying organic matter where the oxygen is depleted to low levels by the active microorganisms present. Woldendorp (1962) has also reported that losses of nitrogen are greater in the rhizosphere where there is a high demand for oxygen by both the roots and the rhizosphere microorganisms that are feeding on root exudates and cell debris. There is still much need for more quantitative data on the various aspects of denitrification in soils that are ordinarily considered as well aerated.

CHEMICAL DECOMPOSITION OF NITROUS ACID

Nitrous acid is, as already pointed out, an intermediate nitrification product formed chiefly by the bacterium *Nitrosomonas* from ammonia. In fertile soils the population of this bacterium is usually sufficiently large for the oxidation of the ammonia to proceed as rapidly as it is produced from organic matter. The next step in the nitrification process, the oxidation of nitrous acid to nitric acid by the bacterium *Nitrobacter*, is also a comparatively rapid one in productive soils. Under reasonably normal conditions, then, there is no accumulation of either ammonia or nitrous acid. Under some conditions, however, this normal oxidation process may not go to completion but is interrupted at the nitrous acid stage.

The primary cause of the blocking of nitrous acid oxidation is the accumulation of abnormal amounts of ammonia, which is toxic to *Nitrobacter* if present in considerable concentration. The toxic concentration has not been determined accurately and will vary widely with the sorptive characteristics of the soil, with its pH, and with the rate at which *Nitrosomonas* is able to oxidize it to nitrites. In practice, such toxic concentrations are most likely to be encountered when very large amounts of succulent, highly nitrogenous, green manures are incorporated in a soil, and when large amounts of ammonia fertilizer, especially anhydrous ammonia, and ammonia solutions are applied. Under experimental greenhouse conditions where abnormally large amounts of green manures are sometimes applied, it is not unusual to observe an inhibition of nitrate formation. Under ordinary field conditions such inhibition is seldom observed because the green manure added is usually in too small amounts, too carbonaceous, or too woody to serve as a source of toxic amounts of ammonia. Under these more normal conditions *Nitrosomonas* would be able to oxidize the ammonia as fast as produced.

The greatest danger of encountering ammonia toxicity to *Nitrobacter* is of course following addition of large amounts as fertilizer to limited areas of the soil, as in the band application of anhydrous ammonia or ammonium solutions. Under such conditions sterilization, or at least partial sterilization, is likely to occur at the point of application. Since the nitrifying bacteria are especially sensitive to unfavorable conditions, they may be completely eliminated in the center of the zone of application. Later this zone will be repopulated with nitrifiers as they move in from the surrounding areas.

When the oxidation of nitrite to nitrate is blocked the nitrite does not always accumulate. In alkaline soils it is chemically stable and usually remains in the soil until it is eventually converted into nitrate (Fraps and Sterges, 1930; Meek and MacKenzie, 1965). In acid soils, especially those below pH 5, nitrite is highly unstable and breaks down chemically to nitric oxide (Allison, 1963, 1966). This gas may be absorbed by or react with the soil, may react with oxygen to form nitrogen tetroxide, or may volatilize. Present inadequate evidence seems to indicate that most of the nitric oxide is retained in the soil and is oxidized to nitrate.

REACTION OF NITROUS ACID WITH SOIL CONSTITUENTS

The reaction of nitrous acid with α-amino acids to form nitrogen gas has long been emphasized as a possible channel of loss of nitrogen to the atmosphere. In this reaction the nitrogen gas evolved is derived in equal quantities from each of the two reacting substances (Allison, 1955, 1966). This reaction, commonly designated as the Van Slyke reaction, is used in the rapid and quantitative determination of amino acids. This analysis is carried out in glacial acetic acid and in an atmosphere of nitric oxide. Under conditions comparable to those found in soil there is now general agreement (Wijler and Delwiche, 1954; Clark et al.,1960; Allison, 1963) that the reaction is of very minor importance. Vanecko and Varner (1955) have shown that it may possibly occur in plant sap if nitrites are present in quantity, but this is seldom the case. In soils, free α-amino acids are extremely scarce, and, furthermore, nitrous acid, if formed, is very unstable in acid soils. Under such conditions the nitrous acid is more likely to decompose to nitric oxide than it is to react with amino acids to form nitrogen gas.

Nitrite can also react with ammonia to form ammonium nitrite which is stable in alkaline media but unstable under acid conditions. It decomposes to liberate nitrogen gas. This reaction, which is similar to or identical with the Van Slyke reaction discussed above, has been emphasized by many workers over the years. There is still little quantitative data that characterize the reaction with respect to concentration, temperature, pH, and effects of catalysts (Wilson, 1943; Allison, 1966). Most recent workers, with the notable exception of Gerretsen and De Hoop (1957), seem to agree that there is no good evidence that loss of gaseous nitrogen via ammonium nitrite decomposition is likely to be a serious channel of loss from soils. Ammonium nitrite is seldom formed in soils in appreciable amounts and, if formed there or added, would more likely decompose as do other nitrites to release nitric oxide rather than molecular nitrogen.

The most striking new development in the field of gaseous loss of nitrogen is the finding that nitrous acid or nitrite can react chemically with soil organic matter with the liberation of a part of the nitrite nitrogen as gases, mostly molecular nitrogen and oxides of nitrogen. The large losses of nitrogen reported by Gerretsen and De Hoop (1957), and attributed by them to the ammonia–nitrite reaction, were according to Smith and Clark (1960) probably the result of the "reduction of nitrite to nitrogen gas by some component of the soil complex." Clark et al. (1960), Clark and Beard (1960) and Tyler and Broadbent (1960) presented evidence at about the same time that seems to be in harmony with this hypothesis. Larger losses of nitrogen from soils containing nitrite usually occurred at pH 5.5 to 6.5 than in more acid soils, probably because the stability of nitrous acid decreases markedly as acidity increases.

Carter and Allison (1961) also observed losses of nitrogen ranging up to 37% when heavy applications of ammonium sulfate were added to acid soils limed to pH 6.6. The mechanism of loss was not determined but in the light of more recent investigations it is quite possible that a nitrite–organic matter reaction was responsible for the gaseous nitrogen loss.

Reuss and Smith (1965) observed a 40% conversion of added nitrite nitrogen to nitrogen gas in 24 h in a sterilized silt loam of pH 4.6; two other soils of lower organic matter content and having a pH of 5.6 lost 12 and 9.5% nitrogen. Some nitric oxide was also evolved. The authors suggest that the nitrogen gas may have been evolved as a result of a reaction of the nitrous acid with labile amino groups in the soil organic matter.

Using the Van Slyke analytical procedure Stevenson and Swaby (1964) observed that nitrous acid reacted with lignin to produce nitrogen gas, nitrous oxide and methyl nitrite. Studies reported by Führ and Bremner (1964) showed that added nitrite is fixed, probably as nitroso compounds, by sterile soils over the pH range of 3 to 7, the fixation decreasing as neutrality was approached. At the same time 33 to 79% of the added nitrite nitrogen was lost, presumably as nitrogen gas, nitrous oxide and nitric oxide.

In more recent studies conducted in the absence of oxygen and in aqueous solutions buffered at pH 6 and 7, Stevenson et al. (1970) identified N_2, N_2O, NO and CO_2 in gases formed by reacting nitrous acid with soils, humic and fulvic acids, lignins, lignin-building units, and polyphenols. The largest amounts of N_2 were produced as a result of the reaction of nitrite with humic and fulvic acids; methyl nitrite was not detected. The authors state that "the findings of this study emphasize the complexity of "chemical denitrification" processes and suggest that a whole series of reactions may take place when NO_2^- accumulates in soil." They state that although many factors affect the magnitude of loss of nitrogen through nitrosation reactions, "an imperceptible slow evolution of N gases could result in significant losses of fertilizer N on a per acre-year basis."

The results of these groups of investigations would seem to leave no doubt that nitrite or nitrous acid can react with lignin or lignin-like compounds with the simultaneous release of some forms of gaseous nitrogen but the practical importance of these reactions is still in doubt. While nitrite is being formed constantly in soils from ammonia, it is only under rather unusual soil conditions that it is present in appreciable concentrations. The fact that some gaseous nitrogen may be released does, however, help to explain why it is only rarely that all of the added fertilizer nitrogen can be accounted for in the crop and soil.

REFERENCES

Allison, F.E., 1955. *Adv. Agron.*, 7: 213–250.

Allison, F.E., 1963. *Soil Sci.*, 96: 404–409.

Allison, F.E., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 573–606.

Allison, F.E., 1966. *Adv. Agron.*, 18: 219–258.

Arnold, P.W., 1954. *J. Soil Sci.*, 6: 116–128.

Ashley, D.A., Bennett, O.L., Doss, B.D. and Scarsbrook, C.E., 1965. *Agron. J.*, 57: 370–372.

Bennett, H.H. and Lowdermilk, W.C., 1938. In: *Soils and Men. Yearbook of Agriculture, 1938.* U.S. Dep. Agric. U.S. Govt. Printing Office, Washington, D.C., pp. 581–608.

Blake, G.R. Allred, E.R. and Van Bavel, C.H.M., 1960. *Minn. Agric. Exper. Stn., Tech. Bull.*, 235: 1–36.

Boawn, L.C., Nelson, C.E., Viets Jr., F.G. and Crawford, C.L., 1960. *Wash. Agric. Exper. Stn., Bull.*, 614: 1–24.

Börner, H., 1960. *Bot. Rev.*, 26: 393–424.

Broadbent, F.E. and Nakashima, T., 1967. *Soil Sci. Soc. Am., Proc.*, 31: 648–652.

Burns, G.R. and Dean, L.A., 1964. *Soil Sci. Soc. Am., Proc.*, 28: 470–474.

Burstrom, H., 1945. *Ann. R. Agric. Coll., Swed.*, 13: 1–86.

Cady, F.B. and Bartholomew, W.V., 1960a. *Soil Sci. Soc. Am., Proc.*, 24: 477–482.

Cady, F.B. and Bartholomew, W.V., 1960b. *Soil Sci. Soc. N.C., Proc.*, 3: 44–51.

Carter, J.N. and Allison, F.E., 1961. *Soil Sci. Soc. Am., Proc.*, 25: 484–486.

Carter, J.N., Bennett, O.L. and Pearson, R.W., 1967. *Soil Sci. Soc. Am., Proc.*, 31: 50–56.

Clark, F.E. and Beard, W.E., 1960. *Trans. Int. Congr. Soil Sci., 7th, Madison, Wisc., 1960, Comm.*, III: 501–508.

Clark, F.E., Beard, W.E. and Smith, D.H., 1960. *Soil Sci. Soc. Am., Proc.*, 24: 50–54.

Dilz, K. and Woldendorp, J.W., 1960. *Proc. Int. Grassland Congr., 8th, 1960*, pp.150–152.

Frank, H., 1954. *Planta*, 44: 319–340.

Fraps, G.S. and Sterges, A.J., 1930. *Tex. Agric. Exper. Stn., Bull.*, 412: 1–15.

Führ, F. and Bremner, J.M., 1964. *Landwirtsch. Forsch.*, 18: 43–51.

Gardner, W.R., 1965a. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 550–572.

Gardner, W.R., 1965b. *Am. Rev. Plant Physiol.*, 16: 323–342.

Gerretsen, F.C. and De Hoop, H., 1957. *Can. J. Microbiol.*, 3: 359–380.

Greenland, D.J., 1962. *J. Agric. Sci.*, 58: 227–231.

Jones, E.J., 1951. *Soil Sci.*, 71: 193–196.

Krantz, B.A., Ohlrogge, A.J. and Scarseth, G.D., 1944. *Soil Sci. Soc. Am., Proc.*, 8: 189–195.

Lipman, J.G., Blair, A.W. and Prince, A.L., 1928. *Soil Sci.*, 26: 1–25.

Lipman, J.G. and Conybeare, A.B., 1936. *N.J. Agric. Exper. Stn., Bull.*, 607: 1–23.

McKee, H.S., 1949. *New Phytologist*, 48: 1–83.

Massey, H.F. and Jackson, M.L., 1952. *Soil Sci. Soc. Am., Proc.*, 16: 353–358.

Meek, B.D. and MacKenzie, A.J., 1965. *Soil Sci. Soc. Am., Proc.*, 29: 176–178.

Meek, B.D., Grass, L.B. and MacKenzie, A.J., 1969. *Soil Sci. Soc. Am., Proc.*, 33: 575–578.

Meek, B.D., Grass, L.B., Willardson, L.S. and MacKenzie, A.J., 1970. *Soil Sci. Soc. Am., Proc.*, 34: 235–239.

Moe, P.G., 1967. *Soil Sci. Soc. Am., Proc.*, 31: 380–382.

Moe, P.G., Mannering, J.V. and Johnson, C.B., 1967. *Soil Sci.*, 104: 389–394.

Moe, P.G., Mannering, J.V. and Johnson, C.B., 1968. *Soil Sci.*, 105: 428–433.

Mortland, M.M., 1958. *Adv. Agron.*, 10: 325–348.

Neal, O.R., 1944. *J. Am. Soc. Agron.*, 36: 601–607.

Nõmmik, H., 1956. *Acta Agric. Scand.*, 6: 195–228.

Overrein, L.N., 1968. *Soil Sci.*, 106: 280–290.

Overrein, L.N., 1969. *Soil Sci.*, 107: 149–159.

Pearson, R.W., Jordan, H.V., Bennett, O.L., Scarsbrook, C.E., Adams, W.E. and White, A.W., 1961. *U.S. Dep. Agric., Tech. Bull.*, 1254: 1–19.

Prince, A.L., Toth, S.J., Blair, A.W. and Bear, F.E., 1941. *Soil Sci.*, 52: 247–261.

Reuss, J.O. and Smith, R.L., 1965. *Soil Sci. Soc. Am., Proc.*, 29: 267–270.

Rovira, A.D., 1962. *Soils Fert.*, 25: 167–172.

Russell, E.J., 1950. *Soil Conditions and Plant Growth.* Longmans Green, New York, N.Y., 8th ed., 635 pp.

Shaw, K.S., 1962. *J. Agric. Sci.*, 58: 145–151.

Simpson, J.R. and Freney, J.R., 1967. *Aust. J. Agric. Res.*, 18: 613–623.

Smith, D.H. and Clark, F.E., 1960. *Soil Sci.*, 90: 86–92.

Stallings, J.H., 1957. *Soil Conservation.* Prentice-Hall, Englewood Cliffs, N.J., 575 pp.

Stevenson, F.J., Harrison, R.M., Wetselaar, R. and Leeper, R.A., 1970. *Soil Sci. Soc. Am., Proc.*, 34: 430–435.

Stevenson, F.J. and Swaby, R.J., 1964. *Soil Sci. Soc. Am., Proc.*, 28: 773–778.

Stoltenberg, N.L. and White, J.L., 1953. *Soil Sci. Soc. Am., Proc.*, 17: 406–410.

Tyler, K.B. and Broadbent, F.E., 1960. *Soil Sci. Soc. Am., Proc.*, 24: 279–282.

Van Bavel, C.H.M., 1959. *U.S. Dep. Agric., Tech. Bull.*, 128: 1–38.

Van Bavel, C.H.M. and Lillard, J.H., 1957. *Va. Agric. Exper. Stn., Tech. Bull.*, 128: 1–38.

Van Bavel, C.H.M. and Verlinden, F.J., 1956. *N. C. Agric. Exper. Stn., Tech. Bull.*, 122: 1–60.

Vanecko, S. and Varner, J.E., 1955. *Plant Physiol.*, 30: 388–390.

Volk, G.M., 1959. *Agron. J.*, 51: 746–749.

Wagner, G.H. and Smith, G.E., 1958. *Soil Sci.*, 85: 125–129.

Ward, H.S., Van Bavel, C.H.M., Cope, J.T., Ware, L.M. and Bouwer, H., 1959. *Ala. Agric. Exper. Stn. Bull.*, 316: 1–53.

Wetselaar, R., 1962. *Plant Soil*, 16: 19–31.

Wijler, J. and Delwiche, C.C., 1954. *Plant Soil*, 5: 155–169.

Wilson, J.K., 1943. *N. Y. (Cornell) Agric. Exper. Stn., Mem.*, 253: 1–36.

Woldendorp, J.W., 1962. *Plant Soil*, 17: 267–270.

FUNCTIONS AND EFFECTS OF ORGANIC MATTER IN MINERAL SOILS

Chapter 14

A SOURCE OF INORGANIC NUTRIENTS AND MICROBIAL FOOD

INTRODUCTION

Organic matter is the center of nearly all life activities in the soil including that of the microflora, the fauna, and the root systems of higher plants. It is true that plants can make normal growths in inorganic solid media, and even in liquid cultures containing no organic matter, if the essential inorganic materials are supplied. The growing of plants in these artificial systems (sand or liquid cultures) is, however, a rather tricky procedure and usually requires much attention to detail if full success is to be attained. Certainly such systems are not suited to the mass production of food for the world population. There are many benefits (Whitehead, 1963) that are derived from the presence of organic matter in soil, as is brought out in the various chapters of this book, but of first importance is the fact that it is a source of food for the various forms of life that are found in soils. The term food is used here in the broad sense to include both plant nutrients and organic energy sources.

The plant nutrients comprise the inorganic elements that are required for plant growth; most of them are also essential for the life of microflora and fauna. The energy sources include the organic compounds in soil that are subject to biological attack and thereby serve as energy sources for the soil fauna and microflora other than the few bacteria that can live autotrophically. Even the autotrophs may benefit from the presence of organic matter since they require carbon dioxide which is derived in part from soil organic matter.

ESSENTIAL ELEMENTS

The essential elements are usually divided into macronutrients and micronutrients. The macronutrients, as commonly listed, include nine elements, namely, oxygen, hydrogen, carbon, nitrogen, phosphorus, potassium, sulfur, calcium and magnesium. There is some uncertainty as to the essentiality of some of the micronutrients but those generally required include iron, copper, manganese, zinc, boron, chlorine and molybdenum. In addition, cobalt, vanadium, sodium and chlorine are required by some microorganisms, but are probably not essential for higher green plants. Strictly speaking, not all of these are obtained from soil organic matter but it should be emphasized that any one or all of them may be a part of the organic matter at some time. This is obvious since they are, or may be, present in plant and animal tissues that find their way into the soil and, as a result of decomposition processes, are either released or may become even more tightly bound in humus.

The classification of essential elements into macro- and micronutrients has little biological significance. These terms, as the names suggest, reflect in a broad sense the relative quantities of the elements usually needed for optimum growth by most species of higher plants. Actually, the need for any particular element, especially of some of the minor elements, often varies widely among plant genera and species. The more important factors, scientifically, are whether a given element is really essential, and what its function in nutrition is. Of course in practical use the quantity required is commonly very important since the agronomist's task is to supply the optimum amount required under varying soil conditions without running into toxicity effects as rainfall and temperature vary.

In the discussion that follows reference will be made in a general but incomplete way to the function of the essential elements in life processes. In the case of some of these elements there is considerable doubt as to their exact roles in plant growth, and also some differences in opinion among investigators. Further information on this is available in textbooks dealing with plant physiology and soil fertility (see Russell, 1961, Tisdale and Nelson, 1966) as well as in many journal articles such as those of McMurtrey Jr. and Robinson (1938), Hewitt (1951), McElroy and Nason (1954), Starkey (1955), Gauch (1957), Broyer and Stout (1959), Nicholas (1961), Bollard and Butler (1966), Evans and Sorger (1966). The aim here is to emphasize the importance of soil organic matter as a direct and indirect source of these nutrients.

Macronutrients

Carbon, hydrogen and oxygen

Protein, which is the seat of most of the life activities of plants and animals, contains carbon, hydrogen, oxygen, nitrogen, phosphorus and sulfur. The first three of these elements are obtained by green plants from water and carbon dioxide, and hence nature is largely responsible for supplying these non-mineral elements. Man can assist nature by engineering operations that provide either irrigation or drainage. A little more carbon dioxide may be provided by maintaining a high level of organic matter in the soil but there is considerable doubt as to the magnitude of this effect. Present evidence shows that a small percentage of the carbon dioxide can enter the root from the soil but the main channel of entrance is through the leaves (Livingston and Beall, 1934; Kick et al., 1965; Sauerbeck and Führ, 1966). Since this is true, most of the carbon dioxide released from any given soil escapes to the atmosphere and is commonly utilized only in small part by the crop growing on this soil. However, when the foliage is dense near the soil surface, and the wind velocity is low, the released carbon dioxide may be trapped long enough for a considerable portion of it to be used in photosynthesis.

Nitrogen

Crop yields are commonly limited more by an inadequate supply of nitrogen than of any other element and hence this element occupies a unique economic, as well as metabolic, position. Not only is it needed in comparatively large amounts for plant growth, but it is fairly expensive to supply and easily lost from the soil by leaching or in gaseous forms. The seeds of our common grains, such as corn, wheat and oats, contain 10–12% protein or nitrogen equivalent. Approximately a third of the weight of soybeans consists of protein. Dry corn stover usually contains 3.5–4.0% protein, timothy has 5.0–6.0%, and bluegrass hay 7–8%. Cotton-seed meal contains about 45% protein. The nitrogen content of these plant materials is obtained by dividing the protein contents by 6.25.

Although it is common practice to express the nitrogen content of plant products, such as mentioned above, as protein, the nitrogen is not all present in this form. Some is present as nucleoproteins, amino acids, amino sugars, polypeptides and small amounts of many other compounds. The nitrogen in storage organs and mature tissues is likely to be there chiefly as protein but in actively growing tissues the percentage that is present as protein is usually much less.

Some of the protein nitrogen is in the form of enzymes which are the active agents in metabolic or growth processes of the plant. Much of the nitrogen in plant proteins is not fixed as structural material but is highly labile, and constantly undergoes degradation followed by synthesis into other compounds to meet the needs of cells at different periods of the plant's growth. Nitrogen in the form of comparatively simple compounds may move from cell to cell as the need arises. Since protein in the form of enzymes, nucleoproteins, etc., is the center of all life processes it is obvious that normal growth cannot occur when it is in deficient supply. If nitrogen is abundant there is less tendency for movement within a plant, but when it is deficient it is a common observation that nitrogen compounds are very mobile. The movement is from the older tissues to the more active growth centers, especially into the succulent green shoots. In seed plants there is also a movement into the storage organs as the plant begins to approach maturity.

Nitrogen is also a constituent of chlorophyll which is a key material in the conversion of sunlight into sugars, starch, cellulose, proteins, and other energy-containing substances. An adequate level of nitrogen makes possible a high level of chlorophyll and a deep green leaf color instead of a yellow tint that commonly denotes a deficiency of this element.

The main source of nitrogen for plant growth is soil organic matter. Inorganic soils, as pointed out in Chapter 7, ordinarily contain about 400–6,000 lb. of nitrogen in the plowed layer and large amounts, but lower percentages, in the subsoils. Soil humus usually contains about 5.0–5.6% nitrogen and 50–58% carbon. The carbon–nitrogen ratio is commonly within the range of 9–12 but may be as high as 18 or occasionally even higher. The wider ratios are likely to reflect incomplete decomposition of very woody-type vegetation. Where burning of the vegetation is a common practice, as in parts of the Tropics, high carbon–nitrogen ratios in soils may be due to the presence of elemental carbon which is not a part of soil humus.

The amount of nitrogen released from soils of similar type is usually closely related to the amount of nitrogen or organic matter in the soil. This is illustrated in Fig.14.1 taken

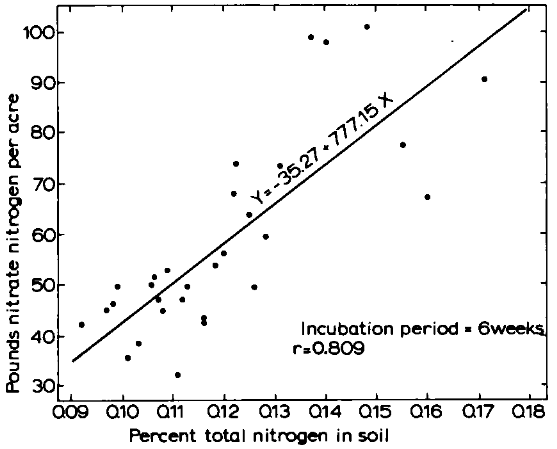

Fig. 14.1. Nitrate formation in relation to total soil nitrogen. (From Allison and Sterling, 1949.)

from the publication of Allison and Sterling (1949). These nitrification tests were made on South Dakota soils from long-time fertility plots that had received various cropping treatments.

Sources of nitrogen for plant use, other than soil organic matter and traces released from rocks, include the small amounts fixed from the air by free-living microorganisms and the larger amounts fixed by legumes (and nonlegumes) that live in symbiosis with microorganisms (see Chapter 10). These natural sources of nitrogen are supplemented by large amounts of commercial fertilizers. Under intensive systems of agriculture synthetic nitrogen materials are often the chief nitrogen source.

Nearly all of the nitrogen in soil organic matter is unavailable to plants until it is converted by microorganisms into ammonia and nitrates. A few simple organic compounds, such as urea and amino acids, may be assimilated directly but the amount so absorbed is a small percentage of the total. The bulk of the nitrogen in the soil that is in organic form must undergo hydrolysis to ammonia before it is utilizable by plants. Some of this ammonia, if not assimilated by microorganisms or higher plants, is quickly converted to nitrate. In the oxidation of ammonia, nitrite is formed but fortunately it seldom accumulates; it is toxic to most plants at comparatively low concentrations. Both ammonia and nitrate are excellent sources of nitrogen but more care must be used when ammonia is the sole source of nitrogen to make certain that basic materials are present in adequate quantities. Since nitrogen as ammonia enters a plant root as a basic ion it replaces in part other basic ions, and this always introduces the possibility that the plant may suffer from deficiency of one or more basic elements, or from lack of proper ion balance. With increasing soil acidity the possibility of malnutrition increases (see Chapter 23).

Soil organic matter constitutes a nitrogen reservoir that is never completely empty and yet seldom full enough to provide enough of the element to permit maximum growth of most common crops. As pointed out in a previous chapter, soil organic matter consists of humic and nonhumic substances. Much of the humic material appears to be spherical, acidic, high-molecular-weight, phenolic-amino acid cross-linked polymers that are broken down in soil only very slowly. As shown by carbon dating, some of this humic nitrogen may remain in soils for 3,000 years or longer. This fraction is therefore of essentially no value as a source of nitrogen for crops. It is the nonhumic substances, sometimes designated as active organic matter, that are constantly undergoing decomposition at various rates that release nitrogen for plant use. This active organic matter consists of plant and animal residues that have been formed in, or added to, the soil largely during the previous 25 years, and mostly during the previous 1 to 5 years. As these materials decompose, a constant trickle of available nitrogen is released to growing crops. The fact that soil organic matter does furnish such a constant supply of available nitrogen constitutes one of the main benefits derived from its presence.

Plants tend to assimilate most of the supply of nitrogen available to them during the early stages of growth; they literally gorge on the nitrogen if it is abundant. This excess nitrogen may meet the needs of the plant for several days but a steady and continuing growth can take place only if nitrogen continues to be made available. This need under ideal conditions is met by soil organic matter. If a pasture crop is being grown the nitrogen needs do not decrease much with time for the obvious reason that the crop is not allowed to reach maturity. The succulent growth continues as long as climatic conditions are favorable.

Under laboratory conditions with no crop present it is not unusual to observe that as much as 5–10% of the nitrogen in soil organic matter may be converted into nitrates within a 6-month period. This is illustrated in Fig.14.2 drawn from the data reported by

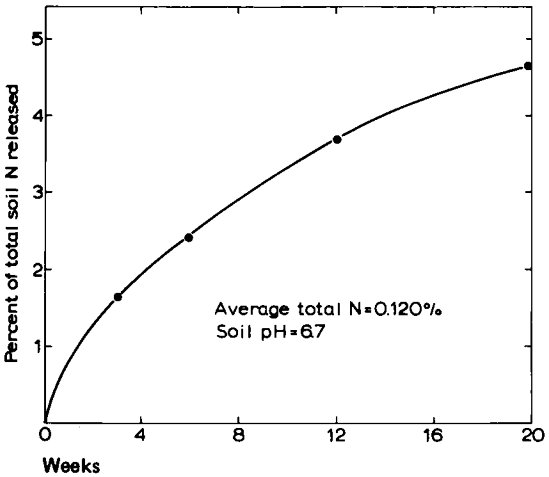

Fig.14.2. Trend of nitrate formation from soil organic matter under laboratory conditions. (From Allison and Sterling, 1949.)

Allison and Sterling (1949). The rate of release decreases rapidly with time after the first 1 to 3 months. Under field conditions the percentage of soil nitrogen released annually to a cultivated crop varies widely. A corn crop grown on a fertile loam is likely to remove about 1.5–3.0% of the nitrogen in the plowed layer during a single year. If the soil is very sandy, and hence low in organic matter, the nitrogen removal may be as high as 6%. Aside from climatic conditions, the type and amount of crop residues recently added to the soil are important factors determining nitrogen release. Recent additions of succulent legumes will increase the release, whereas residues, such as straw and corn stover, tend to immobilize a part of any nitrogen that would in their absence be made available as ammonia.

Phosphorus

Soil organic matter is an important source of phosphorus for plants, usually constituting 15–80% of the total phosphorus in soil (Mortensen and Himes, 1964). Our better soils commonly contain at least 25–50% of their phosphorus in the organic fraction (Pearson and Simonson, 1939; Bower, 1949; Kaila, 1963). Usually the amounts vary directly with the amounts of carbon and nitrogen, and according to Black (1957) increase as the pH decreases. Black and Goring (1953) state that carbon, nitrogen and phosphorus in soil organic matter are roughly in the ratio 110:9:1 in mineral soils and wider in organic soils. This ratio varies so widely, however, that it has little significance. The amount of organic phosphorus usually decreases gradually with depth, as does total organic matter. Black and Goring (1953) state that although a surface horizon may contain 300–400 p.p.m. of organic phosphorus the amount at a depth of 3 ft. is seldom more than 30 p.p.m. The immediate source of this phosphorus is of course plants and animals, but after undergoing extended decomposition it is generally considered that little of these materials remain. Soil organic phosphorus is therefore chiefly microbial phosphorus.

Black (1968) reviewed briefly the present status of our knowledge of the chemical nature of the organic phosphate of soils and concluded that "if the identified organic phosphorus is summed, one has about 2% of the total present in nucleic acids, 1% in phospholipids, and 35% in inositol phosphates, making a total of 38% accounted for. The nature of the remainder is unknown." (Also see Cosgrove, 1967.) Much further research, initially on methods, will be needed before the organic phosphorus can be characterized with any satisfactory degree of exactness.

Organic phosphorus compounds in soils behave very much as do organic nitrogen substances with respect to decomposition. In both cases there are active and inactive forms of the two elements. The active substances are chiefly the portions of the residues that have not yet been transformed into microbial substances. The inactive forms of phosphorus behave very much as do the inactive forms of nitrogen that we call humic acid, but the explanation for the biological inactivity may not be, and probably is not, the same for the two types of constituents.

In the case of phosphorus there is no certainty as to the reasons for the inactivity. Some of the phosphorus is present in bacterial cells that are quite resistant to biological attack. Some of the organic compounds, such as phytin, form salts with calcium, iron and aluminum and these have a very low solubility. Clays with expanding lattices will also adsorb some of these compounds and protect them against biological attack. Since little is known about the chemical nature of soil organic phosphates any explanation offered can be little more than a hypothesis.

Quantitative studies of the release from soils of organic phosphorus, as distinct from inorganic phosphorus, are very scarce for the reason that the two forms of soil phosphorus always occur together. There are numerous data on the release of available phosphorus from soils under various conditions but usually one cannot be certain as to the origin of the released phosphorus, that is, from organic or inorganic forms. Van Diest and Black (1959a,b) studied this problem and concluded that a substantial amount of the organic phosphorus is released to growing plants from soil organic matter during a growing season. Certainly no other conclusion would be expected from studies made with normal productive soils. Rhoades (1939) observed that the addition of crop residues and manure to alkaline soils resulted in an increase in soluble phosphorus but this phosphorus was derived largely from the organic materials and not from native soil phosphorus.

Research is also handicapped by the fact that most of the released phosphoric acid is likely to be fixed immediately as insoluble and largely unavailable salts of calcium, iron and aluminum. Any crop present will assimilate a portion of the phosphoric acid as it is released but in clay soils most of it is fixed in inorganic forms. In the case of actively decomposing plant materials in soil the phosphorus content of the material undergoing decomposition is a major factor in determining what happens to the released phosphorus. There is a critical C:P level here just as there is a critical C:N level in the case of decomposing nitrogenous substances.

Plants can absorb some soluble organic phosphates, such as phytin and nucleic acid that may be formed from organic matter, but such substances are so readily attacked by microorganisms that it is doubtful if direct absorption of these phosphates occurs to any appreciable extent in soils. Most of the phosphorus undoubtedly enters the root as the primary orthophosphate ion, $H_2PO_4^-$, but a lesser amount may be absorbed as the secondary orthophosphate ion, HPO_4^{2-}. A low pH favors the uptake of the primary form and a higher pH favors the absorption of the secondary ion. Unlike nitrate, which is reduced when utilized by plants, phosphate remains in the oxidized state in organic combinations.

Phosphorus does not remain fixed in plant tissues but moves about from cell to cell where needed. If the total supply in a plant is limited it will move readily from the older tissues to the actively growing centers. This is in line with its essential role in energy transfer processes that are so much a part of the metabolic processes involved in growth. A marked phosphate deficiency in a plant may produce a marked stunting of growth but few other evidences of lack of phosphorus except possibly a reddish pigmentation in the leaves.

Organic phosphate is constantly being synthesized in soils by microorganisms that assimilate small amounts of inorganic phosphorus (Goring, 1955). This inorganic phosphorus in unfertilized soils consists chiefly of the insoluble salts of calcium, iron and aluminum, with some fluorapatite and hydroxyapatite. Microorganisms make these compounds available chiefly by secretion of numerous organic and inorganic acids, especially nitric, that can under some conditions dissolve small amounts of the natural phosphates. If higher plants are present the microorganisms and higher plants compete for the phosphorus made available. Some of the organic acids may act as chelating agents that form complexes with various basic elements, thereby releasing the phosphorus in available form. The amount of inorganic phosphate solubilized and converted into organic microbial phosphate is, in the absence of higher plants, usually closely related to the available energy supply. Considerable caution is necessary, however, in the interpretation of such data if the energy sources also contain phosphorus that is released much more readily than is inorganic phosphorus. In the rhizosphere where the most solubilization takes place the microorganisms and higher plants compete for the soluble phosphorus, and doubtless the plants get the major share of it.

The absorption of soil phosphorus by plants is affected by the abundance of other nutrients, particularly nitrogen (Grunes, 1959). This is believed to be due chiefly to the increased growth of the plants, especially of the roots, resulting from nitrogen fertilization. Such roots seem to have an increased foraging capacity for phosphorus. Since both nitrogen and phosphorus are very active in meristematic tissues it is not surprising that there is some associative action, or mutual effects, between them. It has also been observed that ammonium nitrogen frequently increases phosphorus uptake more than does the nitrate form. This may well be largely a matter of ion balance; the cation NH_4^+ and the anion $H_2PO_4^-$ should enter plant cells readily, whereas NO_3^- and $H_2PO_4^-$ are competitors and would require balancing cations that may not be available in sufficient amounts.

There are many statements in the literature to the effect that the addition of farmyard *manures and green manures will increase the availability of soil phosphorus to plants* (Dalton et al., 1952; Stanford and Pierre, 1953). Experimental evidence that supports such statements is, however, very scarce. This effect has been attributed in part to increased carbon dioxide production. It has also been shown that water extracts of decomposing plant materials are more effective in extracting soil phosphorus than is water. It has been suggested that phosphorus may form a complex with humus. More likely the organic matter acts as a chelating agent and removes bases from insoluble phosphate salts. A further suggestion is that humus colloids form a protective coating over sesquioxides, and thereby curtail the fixation of any phosphate that may be made available.

For a rather extensive review of the status of our chemical and agronomic knowledge of soil phosphorus, including both organic and inorganic forms, reference should be made to the publication by Larsen (1967).

Potassium

Potassium occurs in soil: (1) in aqueous solution; (2) adsorbed on organic or inorganic colloids; (3) in the form of insoluble inorganic compounds; and (4) as a constituent of organic residues and living microorganisms (Mulder, 1950). Plants absorb their potassium as the K^+ ion from the soil solution and from the exchange complex. As these reservoirs of available potassium are being depleted they are replenished primarily by potassium being released from insoluble inorganic compounds and from added organic residues. Under many conditions it is the potassium in these residues that is primarily responsible for the maintenance of comparatively large amounts of exchangeable potassium in the topsoil.

Microorganisms assimilate appreciable amounts of potassium but there is little evidence that this element is fixed in the cells in forms that cannot be easily extracted. This subject is discussed by Reitemeier (1951). He states that attempts to demonstrate fixation of potassium by soil organic matter, apart from uptake by microorganisms, have usually yielded negative results.

Some plants, such as spinach and tobacco, will absorb even larger amounts of potassium than of nitrogen when the available supply is large. The exact role of potassium has not been determined with certainty but the evidence indicates that it functions in a variety of ways (Evans and Sorger, 1966). Hewitt (1951) expressed the opinion that it helps to maintain cell organization, hydration and permeability and hence directly or indirectly influences many enzyme systems. It may also help to maintain available supplies of iron, which is so essential in chlorophyll formation and functioning. Where potassium is deficient it has often been noted that carbohydrates tend to accumulate in plants, presumably because of a disruption of the synthetic metabolism, but a causal relationship has not been established. In cell metabolism there are such close interrelations between potassium, calcium and magnesium that it is difficult to establish the individual roles of each of these elements.

Humus and humic acids are known to hold certain metallic cations very strongly. It is usually stated that humus holds di- and trivalent metabolic cations much more firmly than the alkali metal cations (Russell, 1961). There are, however, some exceptions to this generalization for Russell (1966) states that "humus behaves more like montmorillonitic than kaolinitic clays in the relative tightness of binding of exchangeable potassium compared with exchangeable calcium or magnesium ions." For a given ratio of exchangeable potassium to calcium and magnesium on the exchange complex, plants will tend to take up the divalent ions more strongly from the humic and montmorillonitic colloids than from the kaolinitic. This has the consequence that crops growing on soil high in humus are more likely to respond to potassium fertilizers than if they are growing on kaolinitic soils.

Although there is some difference of opinion as to the tenacity with which humus holds potassium, there is certainly no doubt that by means of the exchange complex it does decrease loss by leaching and prevents inorganic fixation (Nishita et al., 1956a,b). Furthermore, plant residues that are high in potassium also serve as excellent, readily-available, sources of this element. Since this nutrient is not in organic form in plants in the sense that nitrogen, phosphorus, and sulfur are, much of it is available for crop use immediately after the plant residues are added to soil. If not so utilized it may remain for some time in the decaying residues or be adsorbed on the exchange complex.

Sulfur

Although sulfur is not one of the three most important elements supplied in commercial fertilizers it is nevertheless a very essential element, and one that is required in larger amounts than is generally supposed. These amounts vary considerably in different crops but on the average the sulfur needs of plants are near those of phosphorus. The total requirements for sulfur are actually greater than for phosphorus because of the greater losses by leaching.

Sulfur is present in soils in both the organic and inorganic forms. Conservative estimates indicate that 50–70% of the sulfur of soils is in the organic matter. The ultimate source is rock material that releases it slowly in the normal process of weathering. According to Whitehead (1964) most unweathered igneous rocks contain 0.05–3.0% sulfur mainly as sulfides of iron, copper and nickel. Under aerobic conditions these sulfides are oxidized to sulfates which may be either assimilated by microorganisms and higher plants, be adsorbed in the soil, or be leached into the subsoil and drainage waters. In most cultivated soils there is usually a rather close correlation between total sulfur content and organic matter, which indicates that most of the sulfur is present in the organic matter or adsorbed on it. If not so incorporated it tends to leach into the subsoil.

Sulfur also gains entrance to the soil as sulfur dioxide that is either washed out of the atmosphere by rainwater or is directly absorbed by plant leaves. The sulfur dioxide gains entrance to the atmosphere chiefly through the burning of coal and other sulfur-containing substances. Around centers of high industrial activity the concentration of this gas may be sufficient to produce injury to plants. Under anaerobic conditions considerable amounts of volatile sulfides, chiefly hydrogen sulfide and methyl thiol, may be released during the decomposition of biological residues. These are oxidized in the atmosphere to sulfur dioxide, which is readily utilizable in cell metabolism and hence available for rapid conversion into organic sulfur in plants and in the soil.

The chemical nature of organic sulfur in soils has not been determined with any high degree of certainty. Whitehead (1964) states that in the incorporation of sulfur into humus, it is the compounds containing –SH groups, such as cysteine, hydrogen sulfide and methyl mercaptan, that are of most importance. The reactions of –SH groups commonly resemble the reactions of $-NH_2$ groups, and it is possible that nitrogen and sulfur may be stabilized in humus in much the same manner. Cysteine and certain other sulfur-containing compounds are known to react readily with quinones, reducing sugars and aldehydes, but there is no proof that these reactions occur in soils. There is also some evidence (Freney, 1961) that sulfate may be chemically incorporated into organic matter as well as being adsorbed by humus. Since sulfates are assimilated by microorganisms it is possible that some of the sulfur is held in the cells in forms that are rather resistant to decomposition.

Sulfur is absorbed by plant roots largely as the sulfate ion, SO_4^{2-}, but sulfur dioxide and sulfur-containing amino acids may also be utilized. Since amino acids are so readily decomposed by soil microorganisms it is unlikely that any appreciable amount of sulfur enters the plant in these forms. When the sulfate ion enters the root most of it is reduced and incorporated into cell substances in the reduced form but a small part may remain in the tissues as sulfate.

When organic materials are decomposed in soils some of the organic sulfur may be mineralized to sulfate if the amount present is more than adequate to meet the needs of the microorganisms. If the energy source is very deficient in sulfur, then there may be no such release (Barrow, 1961b) and if sulfates are present a reverse process may take place; that is, inorganic sulfur may be converted into organic forms and thereby immobilized. The mineralization–immobilization processes in this case are similar to those that occur with nitrogen. The critical C:S ratio in carbonaceous materials above which immobilization occurs rather than mineralization has been reported to be approximately 50:1 (C:N ratio = 5) but this ratio will vary widely depending on the nature of the carbon source (Barrow, 1961a,b). The N:S ratio in soils commonly varies in the range of 10 to 15 or slightly higher, which is similar to that of the N:P ratio. The microbial transformations of sulfur are discussed in some detail by Starkey (1950, 1956), by Alexander (1961), by Freney and Stevenson (1966), and by Freney (1967).

The organic N:S ratios of comparable soils of varying humus content tend to be relatively constant, and on decomposition of the humus about the same proportion of nitrogen and sulfur is mineralized (Russell, 1966). Under the same conditions there is a tendency for a larger proportion of the nitrogen compounds than of the phosphorus compounds to be mineralized. Obviously the organic phosphorus compounds are more resistant to biological attack than are the organic nitrogen and sulfur compounds, but the exact reasons cannot be known until the chemical nature of the organic phosphorus has been determined.

Sulfur is a constituent of the amino acids, methionine, cystine and cysteine, which are essential in proteins supplied in animal diets. Sulfur is also a constituent of the vitamins, thiamine and biotin, and of glutathione and coenzyme A. It plays an important role in the action of proteolytic enzymes and in oxidation–reduction processes. As a constituent of proteins it is present in cell protoplasm and is therefore of vital importance in cell metabolic processes.

Under conditions of sulfur deficiency plants appear chlorotic, stunted, and often unusually weak. The condition resembles nitrogen deficiency symptoms to some extent but differs from them in that the plants are uniformly chlorotic rather than chlorotic chiefly in the older tissues (Gilbert, 1951). This is evidence of a much lower degree of mobility in plants of this element than of nitrogen or phosphorus. In oil-producing plants, such as soybeans, the oil content is likely to be low if sulfur is deficient. An adequate supply of sulfur is also important in the maintenance of a proper balance between nitrogen and sulfur since both are required in protein synthesis. Where the sulfur supply is deficient, plant growth may be markedly retarded or, if nitrogen is abundant, an excess of non-protein nitrogen, especially nitrates, may accumulate.

Calcium and magnesium

Calcium and magnesium are two very important elements that serve to counteract soil acidity and also perform many important functions in cell metabolism. Like potassium, these elements occur (1) in the insoluble or difficultly-soluble mineral portion of soils that undergoes solution at a very slow rate; (2) adsorbed on the soil exchange complex; and (3) as constituents of organic residues including the microorganisms that are active in their decomposition. Calcium and magnesium can also form complexes with organic matter (Broadbent and Ott, 1957; Schnitzer and Skinner, 1963). A high level of humus is especially important in the maintenance of adequate available supplies of these two elements. Both the organic and inorganic colloids hold the elements in exchangeable form but the content of organic matter in soil is particularly important. This is because it commonly has an exchange capacity of 200–300 milli-equivalents per 100 g of dry matter as compared with values of perhaps 20–100 for inorganic colloids.

Calcium and magnesium, like potassium, enter plant roots in ionic forms (Ca^{2+} and Mg^{2+}). Both the water-soluble forms and the readily exchangeable ions are utilized by plants. All exchangeable Ca^{2+} and Mg^{2+} are, however, not equally available. It has been shown in the case of calcium that as it is removed from the exchange complex the difficulty of removal increases progressively as unsaturation increases. This is especially true for montmorillonitic clays, less in evidence for illitic clays, and still less for kaolinitic clays and humus. Considering the high exchange capacity of soil humus, and the availability of the calcium and magnesium held by this organic colloid, it is obvious that organic matter plays a very important role in supplying crops with these two elements. It is usually in the sandy soils, low in organic matter, that calcium and magnesium deficiencies are first in evidence on plants.

Calcium is, according to Broyer and Stout (1959), a peculiar element in that a large percentage of the soil adsorption complex must be occupied by this element to assure normal plant growth. They state that about 30–35% of the cation exchange complex should be occupied with calcium to insure normal growth, but this varies with the type of complex and with the nature of the other adsorbed ions. Since there are such close interrelations between potassium, calcium and magnesium in cell metabolism, it is necessary to make certain that the supplies of these elements on the exchange complex are kept in proper balance. This can be done by giving proper attention to the type of fertilizer used. Information on nutrient balance is reviewed by Broyer and Stout (1959).

Calcium is important in the growth of meristematic tissues including both shoot and root tips. It frequently accumulates in cell walls and leaves in the form of calcium pectate. Calcium also apparently acts as an activator for certain enzymes and performs other metabolic functions that are not yet clearly defined. It seems to neutralize to some extent the undesirable effects of nutrients in the plant that are either undesirable or absorbed in improper amounts or ratios. Too much calcium may, however, depress the uptake of potassium and magnesium, but unlike these elements it is comparatively immobile in the plant.

Magnesium performs some functions similar to those performed by calcium, such as being a specific activator of plant enzyme systems. It is also a constituent of chlorophyll and hence needed by all green plants. It is also believed to aid in the transport of phosphates in the plant. Presumably this is why it accumulates in oily seeds that contain lecithin, a phosphate-containing fat. Like potassium and nitrogen it is a mobile element and moves from older to younger plant tissues when there is a scarcity of supply.

Organic matter not only plays a direct role as a source of calcium and magnesium, but it is also a food for microorganisms that form carbon dioxide and many organic acids, such as acetic, butyric, lactic and oxalic. These acids react with limestones and other minerals and thereby continually release available nutrients. In the presence of an abundant supply of humus much of the released calcium and magnesium that is not immediately absorbed by plants may be adsorbed by the humus and thereby be prevented from loss by leaching.

Micronutrients

The elements that are known to be needed in small amounts by plants are iron, copper, manganese, zinc, boron, chlorine and molybdenum. These are of direct importance in enzymatic reactions, whereas others may at times play an indirect role by substituting for, or by releasing, elements that are more essential.

Many of these elements are so insoluble that in the absence of humus it is impossible for crops to obtain enough of them for normal growth even though only micro quantities are required. Factors that affect the availability of micronutrients are discussed by Leeper (1952). Humus by means of exchange reactions and chelation mechanisms is able to hold most of them except copper in an available form as they are either released from soil minerals or are added to the soil in plant and animal residues and in fertilizers. The ability of soil humus to hold microelements for a considerable time and release them as needed to crops is undoubtedly one of the most important benefits derived from its presence in soils.

Iron

Iron is a very common element in rocks and soils, yet many plants frequently suffer from iron deficiency. This condition, commonly designated as chlorosis, may be caused by a number of conditions, chief of which are a high pH, high lime, and by an excess of phosphate, copper, manganese, and occasionally other elements (Brown, 1961; Wallace, 1965). Under these various conditions the iron may be unable to enter the plant roots in sufficient amounts, or, if it does enter, it cannot move about readily in the plant sap. The reductive capacity of the root is probably an important factor in iron absorption. The susceptibility of different plant genera, and even of varieties within a genus, to iron chlorosis varies markedly. Apparently the plants that are least likely to suffer from chlorosis are able to keep the iron in a mobile condition, probably by means of chelating substances in the plant sap.

The fact that organic matter plays a very important role in iron availability can be demonstrated readily by adding a humic acid solution, naturally high in iron or reinforced with it, to a culture medium in the greenhouse. This iron humate will supply available iron to plants for a much longer time than will most soluble iron salts (Horner et al., 1934). The organic matter extract doubtless chelates with iron and holds it for a time in a soluble condition such that it can be transported within the plant tissues.

Iron, like many of the micronutrients, is involved in enzymatic reactions. It is a constituent of cytochrome respiratory pigments found in animals, higher plants and microorganisms. These pigments that are involved in intracellular oxidations, are chemically much like hemoglobin, since they are complexes of iron, porphyrin and a protein. Cytochrome-*c* and the iron-porphyrin enzyme, cytochrome oxidase, both take part in cell respiration (Hewitt, 1951), and are probably also involved in photosynthesis. Iron is also required for fixation of elemental nitrogen in free-living and nodule bacteria (Nicholas, 1961).

Microorganisms in soil play a major role in making iron available for higher plants. Iron is not only required as a nutrient by heterotrophic bacteria but there are also species of autotrophs that can obtain their energy by oxidizing ferrous iron to ferric iron. So far as plant nutrition is concerned, the heterotrophic organisms are the more important because through their activities iron may be made either more or less available; it is made more available if ferric iron is reduced to ferrous, and less available if the reverse reaction occurs. In these oxidation–reduction reactions the oxygen supply and availability of energy are controlling factors. Thus, soil organic matter plays an important role not only in iron oxidation and reduction but also forms complexes with any soluble iron that is released.

Carbonic acid evolved from decomposing plant residues plays a role in iron availability. In acid soils this carbon dioxide forms bicarbonates which increase the solubility of iron compounds. In alkaline–calcareous soils, however, the carbon dioxide formed acts to keep the iron in insoluble forms and thus may increase chlorosis. Brown (1961) points out that green manure crops when incorporated into moist calcareous soil often cause severe iron chlorosis to develop in deciduous fruit trees.

Under field conditions in humid regions chlorosis is not likely to be encountered in soils that are well supplied with organic matter unless other elements, particularly copper, are present in abnormally high amounts. On Florida Everglade peat soils, for example, where much copper has been added over the years and where the peat has undergone severe subsidence, a chlorotic condition is often observed. This condition that is sometimes designated as copper toxicity is in reality largely iron deficiency caused by excess copper. Under more normal conditions soil humus will merely adsorb any traces of soluble iron that may be released from native minerals or insoluble salts and hold them rather tenaciously. This iron, whether adsorbed on the exchange complex or held in chelated form, is usually readily available to plants. This is an excellent example of how organic matter in soils can function to greatly improve growth conditions even where the organic matter may not directly supply any plant nutrients. Actually, added biological residues usually do supply nutrients as decay takes place but the residual humus, in addition, serves indirect functions.

Copper

Copper is required by plants in very small amounts and may be directly or indirectly toxic at high levels unless inactivated by the soil. For example, studies conducted in solution cultures in the greenhouse have shown that only one-sixteenth to one-eighth part per million of copper is required to meet the needs of tobacco, and amounts much in excess of these produce a decided stunting of growth. Copper is involved in various enzymatic transformations, being a component of ascorbic acid oxidase, tyrosinase, laccase, monamine oxidase, uricase, cytochrome oxidase, and galactose oxidase (Evans and Sorger, 1966). Copper is absorbed by plants as the cupric ion, Cu^{2+}, and it may also enter the plant as a chelate.

Deficiency symptoms in plants vary with the kinds of plants but commonly leaves become pale, develop a bluish-green cast, and may curl. Copper appears to have some function in chlorophyll formation, which can only be indirect, since the chlorophyll molecule does not contain this element. Young leaf and shoot tips may grow rapidly and have a very deep green color, due to high nitrogen concentration, but growth of the new tissues is retarded and they may soon wither and die. This condition when present in oranges is sometimes described as "dieback". The older leaves of most plants may also appear to be chlorotic, and fruit and grain yields are severely reduced. Wheat and oats are especially sensitive to copper deficiency in soils and these crops may fail entirely (Gilbert, 1952).

Copper deficiencies have been observed most often in plants grown on peat and muck soils but may occasionally be encountered in mineral soils. Even if copper is added to organic soils it usually reacts to form complexes from which plants can obtain the copper only with considerable difficulty. It may either enter the exchange complex or be chelated by the organic matter. In either case it is held very tightly against leaching. Our knowledge of the behavior of copper in both organic and mineral soils is still incomplete and research results with different soils of different reactions do not always agree. Undoubtedly a major factor in soils, and in availability to crops, is the amount of other ions present, especially iron, aluminum, manganese, and molybdenum. In general, present evidence indicates that copper deficiency in sandy soils is likely to be due to absence of the required amount of the element, whereas in soils high in organic matter it is the result of "tie-up" in the organic matter.

When soluble copper salts are added to organic soils most of the copper is fixed in the zone of placement. For this reason toxicity is seldom observed in such soils even where hundreds of pounds per acre are added (Gilbert, 1952). Most medium-textured mineral soils can also fix copper but in much smaller amounts. The higher the percentage of organic matter in mineral soils the greater is the capacity for fixation of copper.

Organic matter may, therefore, play either a beneficial or an inhibitory role in copper nutrition depending on the soil, the copper source, and the amount applied. Fresh crop residues added to mineral soils will furnish available copper that the crop can feed on before it is inactivated in the soil. Organic matter in coarse-textured soils will also tend to reduce losses of added copper salts by leaching. Although organic matter can adsorb copper and thus eliminate any possible toxic effects of excess amounts added as a fertilizer or in pesticides it may, on the other hand, sometimes play an objectionable role by so completely fixing copper that the available supply is reduced below the needs of the crop.

Manganese

Manganese is, according to Evans and Sorger (1966), required for the activity of several enzymes including oxidases, peroxidases, dehydrogenases, decarboxylases, and kinases. It also plays a role in photosynthesis, and in nitrite reduction in microorganisms. It is absorbed by plants as the manganous ion, Mn^{2+}, or as a chelate either through the roots or from leaf sprays. It is required in only small amounts, and large amounts may be toxic, especially on acid soils.

Manganese deficiency, which occurs on many crops, usually results in a greying of the young leaves, especially between the veins. This is followed by retarded growth and reduced yields unless manganese is supplied promptly in the form of a spray on the leaves. In oats, manganese deficiency is known as the grey-speck disease, in peas as marsh spot, and in sugar beets as the yellows. This element is comparatively immobile in the plant sap.

Soils that are high in organic matter often produce crops that show manganese deficiency symptoms, particularly if the pH is near neutrality. The organic matter adsorbs any available manganese that is naturally present or added, and the insoluble complexes formed are comparatively stable. This situation is similar to copper fixation but manganese seems to be held a little less tenaciously than is copper.

Microorganisms that use organic matter as a source of energy are also known to be able to oxidize manganese to an unavailable form. This occurs under aerobic conditions in slightly acid soils, and is brought about by various species, but the practical significance of such oxidation is not well understood. In fact, there have been reports of reduction of the higher oxides of manganese following the addition of large amounts of fresh organic materials to soils (Cotter and Mishra, 1968); presumably under these conditions of very heavy growths the combined oxygen serves as a partial substitute for molecular oxygen of the air. Under anaerobic conditions heterotrophic organisms may reduce unavailable manganese dioxide to the manganous form.

Manganese toxicity is sometimes observed on acid soils where the element is most likely to be present in appreciable amounts in the available form. This condition, which can be corrected by liming, is usually less in evidence in soils that are well supplied with organic matter, except possibly at very low pH values. Toxicity or growth inhibition may be due in part to an improper balance of elements in soil, as already noted for other elements. The ratio of soluble iron to soluble manganese has been shown to be especially important; at high ratios there may be manganese deficiency or iron toxicity, whereas at low ratios there may be iron deficiency or manganese toxicity. A somewhat similar boron–manganese relationship has also been emphasized.

The role of soil organic matter in controlling the supply and availability of manganese, and in counteracting toxicity, is, in general, similar to its role in some of the other elements, particularly copper. The behavior of manganese in soils and its relation to plant growth are discussed in some detail by Mulder and Gerretsen (1952).

Zinc

Zinc deficiencies have been observed on many crops grown in various parts of the United States. The first evidences of insufficient zinc are usually chlorosis of the young leaves, stunted rate of growth and in some plants a condition described as rosetting. The element is absorbed by plants as the ion, Zn^{2+}, or as the metal chelate either via the roots or from leaf sprays. It is essential for the growth of some fungi that produce antibiotics, organic acids and pigments.

Zinc functions in plants chiefly as a metal activator of a large number of enzymes (see Evans and Sorger, 1966; Tisdale and Nelson, 1966). Researches to determine the exact role of the element are difficult because of the interrelationships between microelements, and because of the ability of one element to substitute in part for another.

The ability of crops to extract zinc from soils varies rather markedly, alfalfa and certain weeds being very efficient in this respect whereas many cultivated crops are not. It has been suggested that if the zinc-extracting crops are grown and turned under they will provide available zinc for other crops that follow. Although this procedure might be effective it is certainly not economically feasible.

Organic matter does not apparently have as much effect in making zinc less available as it does in the case of copper. In fact, Randhawa and Broadbent (1965) observed that although zinc was more strongly bound on humic acid than was calcium, it was less strongly held than was copper or ferrous iron. Organic matter does play a beneficial role in supplying zinc to plants as needed, particularly on calcareous soils where zinc deficiencies are most often encountered. It would also be expected to be beneficial in soils high in clay minerals of the type that react with, or adsorb zinc, and thereby make it unavailable. It may also act singly, or in conjunction with lime, to reduce zinc toxicity effects on soils that may have excessive amounts of the element, but there is little direct evidence for this.

Boron

Boron is apparently essential for all plants but is needed in only very small amounts. Many plants, especially beans, can tolerate only limited amounts of the element. Its function in plants is still very uncertain but there is considerable evidence that it is involved in cell division, in carbohydrate transport and polymerization, and possibly in nucleic acid metabolism, since a deficiency of the element has been shown to reduce the content of ribonucleic acid (RNA) and desoxyribonucleic acid (DNA). It also seems to play a role in calcium uptake and use in the plant, and in the development and proper functioning of nodules on legumes.

Boron deficiency commonly results in a marked reduction in cell multiplication in the growing tips of shoots and roots. Flower buds, as well as the vascular tissues, may not develop normally, resulting in the browning or death of tissues of crops such as sugar beets and cauliflower. Stems of some plants, such as celery, may become cracked or twisted. According to Tisdale and Nelson (1966) boron is absorbed in various ionic forms, including $B_4O_7^{2-}$, $H_2BO_3^-$, HBO_3^{2-}, or BO_3^{3-}. The element shows little tendency to move from the older plant tissues to the meristematic tissues.

Deficiencies of boron in soils are usually most in evidence in calcareous or over-limed soils, and in sandy soils that are subject to severe leaching. In calcareous soils boron may be held in insoluble forms and also in the cells of microorganisms. There is little evidence that boron is adsorbed to any great extent by soil colloids but they do at least play an indirect role in holding boron by reducing leaching. Plant residues added to soils release much of the boron present as decomposition proceeds, but most of the available boron in soils of humid regions is contained in the organic fraction.

Chlorine

Chlorine has only in recent years been recognized as an essential element for plants. Under ordinary conditions plants usually contain only small amounts of this element but if fertilized with chlorine salts may contain several percent. Our knowledge of the functions of the element is meager. It can at least act as a vehicle for carrying various bases into the plant but so can other anions. It enters the plant as the chloride ion, Cl^- According to Evans and Sorger (1966) it is required for photosynthetic reactions involved in oxygen evolution.

Symptoms of chlorine deficiency are usually not very evident. They include wilting and browning of leaves, some chlorosis, and reduced growth. Excessive quantities lower the smoking qualities of tobacco and the keeping quality of potatoes. Sugar beet leaves may become light green to yellow in color, and the roots show a very stubby growth with many of the roots arising from secondary roots.

Organic matter plays a comparatively small role in holding chlorides against leaching. Neither organic nor inorganic colloids adsorb the ion to any great extent but they do decrease leaching by holding more of the water in the soil. Fresh organic materials would supply available chlorine during their decomposition provided that the plant residues had any appreciable amount initially. There is so little evidence for chlorine deficiency under field conditions that any effect of organic matter is small. This is due in large part to the fact that chlorides are being brought down in the rainfall in amounts greater than plant requirements. Russell (1961) states that at Rothamsted, England, the amount of chloride brought down averages 16 lb. per acre annually. Near the sea the values may be many times this figure.

Molybdenum

Attention has been drawn in recent years to the importance of molybdenum as a result of researches showing its essentiality in both symbiotic and nonsymbiotic nitrogen fixation. Many soils in Australia that formerly yielded only very poor crops of clovers and other legumes were found to yield abundantly when supplied with a few ounces of molybdenum per acre. The growth response is the result of greatly increased nitrogen fixation in the nodules. Molybdenum is also concerned in nitrate reduction in both plants and microorganisms and probably is an activator of other enzymes. It is probably absorbed by plant roots as the ion, MoO_4^{2-}

The symptoms of molybdenum deficiency are usually chlorosis, yellowing of the leaves, and stunted growth (Mulder, 1950; Hewitt, 1951). These are the usual indications of nitrogen deficiency which is the result in this case of decreased nitrogen fixation, and interference with nitrogen metabolism in the cells in the absence of the activator, molybdenum. Plants seem to be able to grow normally without this element if adequate nitrogen is supplied as ammonia.

Most soils contain only very small amounts of molybdenum and this is largely unavailable. Locally in a few dry areas there may be exceptions to this, and plants grown on these soils may contain sufficient molybdenum to cause injury to grazing animals. It is only rarely that injurious effects on crops have been noted from excessive amounts of the element. The addition of large amounts as fertilizer should be avoided primarily because of the effects on the animals that feed on the high-molybdenum vegetation and grains.

There is little information on the effect of organic matter on molybdenum availability but doubtless the same principles apply in regard to this element as to others, as outlined above. The general effect of crop residues and of humus should be favorable through the direct contributions of the former to available molybdenum, and through the effect of the latter in holding the element in available form. Since we are dealing with an anion, MoO_4^{2-}, that is not in organic form there should be little or no tendency for it to be fixed firmly in the colloidal humus. The humus would, however, favor its retention both directly and by its effect in reducing leaching.

Other elements

Besides the 16 elements discussed above that are generally considered to be essential for all higher plants, and for most lower plants, there are several others that are sometimes important. They have been designated as "functional or metabolism nutrients", defined as "any mineral nutrient that functions in plant metabolism irrespective of whether or not its action is specific" (Nicholas, 1961). There are several of these but the chief ones are cobalt, vanadium, sodium and silicon.

Cobalt is a constituent of vitamin B_{12}, which is so essential in animal nutrition. It is also essential for symbiotic and nonsymbiotic nitrogen-fixing bacteria, and may act as an activator of several enzymes. There have been a few reports of responses of nonleguminous plants to the addition of the element.

Vanadium acts as a partial substitute for molybdenum in catalyzing nitrogen fixation by *Azotobacter* and probably other organisms. It is an essential element for the green alga *Scenedesmus* but there is no proof that it is essential for higher green plants. Its role, if any, in plant nutrition is unknown.

Sodium is best known as a partial substitute for potassium, but there is evidence that it also has its own role to play in some plants. Sugar beets, mangolds and celery are known to show a marked response to sodium even where potassium is abundant. Its specific role in plant cell metabolism is uncertain but according to Bollard and Butler (1966) it is definitely essential for at least some higher plants and microorganisms. It is not held strongly by the exchange complex and hence is readily leached from soils. This is often fortunate for sodium is very harmful to soil structure. In semiarid soils it is the most objectionable element that contributes to alkali in soils, and in extreme cases will prohibit most plant growth. Sodium is of course very essential in the blood of animals.

Silicon is present in comparatively large amounts in many grasses, rushes, rice straw and hulls, etc. It is a structural component of diatoms, and most workers have considered that it is essential for these organisms. Its function in plants other than for structural purposes is unknown. In this capacity it does increase resistance to disease. In soils it may increase phosphate availability by displacing it.

Bollard and Butler (1966) in their discussion of functional elements include several others in addition to the above four. They state that fluorine, iodine, and selenium fall in this class for in some plant species they are metabolized, forming definite organic compounds. Bromine, rubidium, and strontium are also placed in this class because they exert a sparing effect on the utilization of chloride, potassium and calcium. Cobalt may perform that same function. They state further that our knowledge of the beneficial effects produced by aluminum, beryllium, and barium are not as yet adequate to justify including these in the group of functional elements. Further research will probably add other elements to this group.

Russell (1961) calls attention to the fact that the supply of available elements in soil can change as a result of changes in the oxidation–reduction status of the soil. Under aerobic conditions, inorganic precipitates, such as those of manganese and iron, may form. These precipitates contain trace element impurities removed from solution during precipitation. Later, with the onset of reducing conditions these precipitates may dissolve and thereby release the impurities. Little is known at present as to the importance of this phenomenon on the supply of available minor nutrients but it is conceivable that a marked change in soil moisture or organic matter status could have considerable effect.

Aside from the effect of active organic matter on solubility of elements, discussed above, it does also directly supply both essential and functional elements, and the organic colloids help to hold them against leaching. It also provides a suitable environment for microorganisms that play an important part in the availability of several of the nutrients, both essential and functional.

MICROBIAL FOOD

The statement has often been made that organic matter is the life of the soil. If taken literally this statement may be questioned since by far the largest portion of soil organic matter, exclusive of living plant roots, represents dead plant and animal substances that have in various ways gained entrance to the soil. But these non-living substances do furnish the energy-yielding materials that make possible a surprisingly large amount of activity on the part of a wide variety of types of microorganisms, both flora and fauna. This teeming mass of life owes its existence almost entirely to chlorophyll-containing plants that utilize the energy of the sun, which is in turn utilized by the soil biological population.

It has already been pointed out that good crops can be grown in inorganic media, or in solutions that are devoid of organic matter, but usually only with considerable difficulty. Organic matter in mixture with minerals, and replenished as crop residues are oxidized, makes it possible for plants to grow under a wide variety of soil conditions that without organic matter would be extremely unfavorable for such plant growth. It is the soil biological population that makes this miracle possible. Without these organisms the added residues would remain largely undecomposed and would soon accumulate to the extent that life on earth as we know it could not exist.

In the early stages of decay of residues there usually occurs a "biological explosion" if the decomposing materials are readily decomposable and conditions are favorable for microbial growth. During this period of a few days or weeks much of the stored-up energy is utilized wastefully. Some nutrients may be released, whereas others may be immobilized in the cells of the microorganisms. The compositions of the residues, environmental conditions, and nature of the microflora and fauna, all enter into the determination of exactly what happens to the nutrients that were initially present in the residues. But after the first flush of decomposition is over, biological activities proceed at a more even rate; in other words, the stage of normal active soil organic matter has been reached.

During the process of decomposition of plant and animal residues there occurs a considerable release of acids, including carbonic, nitric, sulfuric, phosphoric, citric, formic, acetic, butyric, etc. Most of these are weak acids, present in very low concentrations, and the organic acids are soon decomposed to carbon dioxide and water. These acids doubtless have some effect in liberating nutrients from insoluble minerals but there is considerable uncertainty as to the magnitude of the effect. It is probably small in soils that have a fair content of organic and inorganic colloids, for the bases in the exchange complex would neutralize most of the acids as soon as released. Any nutrients released from insoluble minerals would be available for plant use or would be adsorbed by the colloids. Some leaching might occur but a good supply of humus would greatly minimize such losses.

This ability of organic matter to continually supply crops with small increments of available nutrients is possible only through the action of microorganisms that owe their existence to the energy supplied from sunlight through the medium of photosynthesis. A few microorganisms also have the ability to fix atmospheric nitrogen, using the energy supply in the soil. This adds further to the total nutrients available for crop use.

Another important contribution of the soil flora and fauna to soil productivity is through their improvement of soil structure and tilth. Without the energy materials in soil organic matter this benefit often could not be realized. This biophysical aspect of soil fertility is very important in fine-textured soils. A discussion of this phase of microbial activity is given in Chapter 16.

HUMIC SUBSTANCES AS NUTRIENTS

In the early part of the present century there was much interest in, and much research devoted to, the subject of the growth-stimulating effects of rotted manure, compost, and other sources of humic substances. Many of these experiments showed striking increases in plant growth and vigor that apparently could not be attributed to added mineral nutrients, although most of the earlier experiments were too empirical and crude to permit drawing conclusions as to the nature of the stimulating substances. Nevertheless, many workers were rather firmly convinced that certain humic materials are absorbed by plants and produce marked effects on growth. It was this hypothesized growth-promoting effect that seemed to account for some of the marked yield increases frequently obtained with crude humus preparations. Bottomley (1915) was one of many who were very active in this field of research. Bonner (1946) attributed the effects of manure to the nitrogen supplied; no evidence was found to suggest the presence of specific organic substances important in plant growth.

The early observations have now been thoroughly checked by work with humus extracts of much greater purity, as well as with fractions of the humus substances. It is known that crude humus materials, as found in nature, commonly do contain many substances that can markedly increase plant growth. These substances may be ordinary mineral nutrients, or organic substances formed by microorganisms during decay, and sometimes released by plant roots. Such substances may include various vitamins, auxins, amino acids, gibberellins, etc. In many of the earlier experiments the stimulating substances were undoubtedly largely chelated elements, chiefly iron (see Chapter 15). Many mineral elements readily form chelates with humic acids. In the chelated form they continue to remain available for many days and weeks and hence often stimulate growth even in media that contain adequate mineral elements that are not chelated, and hence almost unavailable.

Even-Haim (1966) states that plants are capable of absorbing different organic molecules via roots, and make use of growth factors contained in humified organic molecules, but direct absorption by the plant of humus constituents or lignin decomposition products has never been demonstrated with absolute certainty. Using labelled vanillic acid he demonstrated that under sterile conditions wheat roots absorbed very small amounts of this substance but it was not found in the leaves. Likewise, Führ and Sauerbeck (1966) found that sunflower roots took up only traces of ^{14}C–labelled humic acids and related compounds.

In evaluating the early work it must be borne in mind that not only were impure humic acid preparations used but often the plants were grown in media that were not optimum in all respects. In some cases humic acid preparations may improve the medium and thereby increase plant growth. This would be expected where one or more nutrients are present in excess, or where the nutrient balance is poor. Humic acid, being an excellent buffer and adsorbent, might in such a case increase plant growth following its addition to the medium. Regardless of the various possible explanations for the early results, it is now well established that the pure organic compounds that comprise humic substances or humus do not serve as direct nutrients for higher plants, although it is possible that traces of the smallest humic acid molecules may enter the plant root just as do many other simple organic compounds. Of course if this does occur and humic materials contain some nitrogen, as is generally believed, it is possible that a small part of this nitrogen might be utilized by the plant. Even this is doubtful since the nitrogen in humic acids is so tightly bound.

REFERENCES

Alexander, M., 1961. *Introduction to Soil Microbiology*. Wiley, New York, N.Y., 472 pp.

Allison, F.E. and Sterling, L.D., 1949. *Soil Sci.*, 67: 239–252.

Barrow, N.J. 1961a. *Soils Fert.*, 24: 169–173.

Barrow, N.J. 1961b. *Aust. J. Agric. Res.*, 12: 306–319.

Black, C.A. 1957. *Soil-plant Relationships*. Wiley, New York, N.Y., 332 pp.

Black, C.A., 1968. *Soil-plant Relationships*. Wiley, New York, N.Y., 2nd ed., 792 pp.

Black, C.A. and Goring, C.A.I., 1953. In: W.H. Pierre and A.G. Norman (Editors), *Soil and Fertilizer Phosphorus in Crop Nutrition*. Academic Press, New York, N.Y., pp. 123–152.

Bollard, E.G. and Butler, G.W., 1966. *Ann. Rev. Plant Physiol.*, 17: 77–112.

Bonner, J., 1946. *Bot. Gaz.*, 108: 267–279.

Bottomley, W.B., 1915. *Biochem. J.*, 9: 260–266.

Bower, C.A., 1949. *Iowa Agric. Exper. Stn. Res. Bull.*, 362: 963–996.

Broadbent, F.E. and Ott, J.B., 1957. *Soil Sci.*, 83: 419–427.

Brown, J.C., 1961. *Adv. Agron.*, 13: 329–369.

Broyer, T.C. and Stout, P.R., 1959. *Ann. Rev. Plant Physiol.*, 10: 277–300.

Cosgrove, D.J., 1967. In: A.D. McLaren and G.H. Peterson (Editors), *Soil Biochemistry*. Marcel Dekker, New York, N.Y., pp. 216–228.

Cotter, D.J. and Mishra, U.N., 1968. *Plant Soil*, 29: 439–448.

Dalton, J.D., Russell, G.C. and Sieling, D.H., 1952. *Soil Sci.*, 73: 173–181.

Evans, H.J. and Sorger, G.J., 1966. *Ann. Rev. Plant Physiol.*, 17: 47–76.

Even-Haim, A., 1966. In: *The Use of Isotopes in Soil Organic Matter Studies*. Pergamon, New York, N.Y., pp. 49–59.

Freney, J.R., 1961. *Aust. J. Agric. Res.*, 12: 424–432.

Freney, J.R., 1967. In: A.D. McLaren and G.H. Peterson (Editors), *Soil Biochemistry*. Marcel Dekker, New York, N.Y., pp. 229–259.

Freney, J.R. and Stevenson, F.J., 1966. *Soil Sci.*, 101: 307–316.

Führ, F. and Sauerbeck, D., 1966. In: *The Use of Isotopes in Soil Organic Matter Studies*. Pergamon, New York, N.Y., pp. 73–83.

Gauch, H.G., 1957. *Ann. Rev. Plant Physiol.*, 8: 31–64.

Gilbert, F.A., 1951. *Bot. Rev.*, 17: 671–691.

Gilbert, F.A., 1952. *Adv. Agron.*, 4: 147–177.

Goring, C.A.I., 1955. *Plant Soil*, 6: 26–37.

Grunes, D.L., 1959. *Adv. Agron.*, 11: 369–396.

Hewitt, E., 1951. *Ann. Rev. Plant Physiol.*, 2: 25–52.

Horner, C.K., Burk, D. and Hoover, S.R., 1934. *Plant Physiol.*, 9: 663–669.

Kaila, A., 1963. *Soil Sci.*, 95: 38–44

Kick, H., Sauerbeck, D. and Führ, F., 1965. *Plant Soil*, 22: 99–111.

Larsen, S., 1967. *Adv. Agron.*, 19: 151–210.

Leeper, G.W., 1952. *Ann. Rev. Plant Physiol.*, 3: 1–16.

Livingston, B.E. and Beall, R., 1934. *Plant Physiol.*, 9: 237–259.

McElroy, W.D. and Nason, A., 1954. *Ann. Rev. Plant Physiol.*, 5: 1–30.

McMurtrey J.E. Jr. and Robinson, W.O., 1938. In: *Soils and Men – Yearbook of Agriculture, 1938.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., pp. 807–829.

Mortensen, J.L. and Himes, F.I., 1964. In: F.E. Bear (Editor), *Chemistry of the Soil.* Reynolds, New York, N.Y., 2nd ed., pp. 206–241.

Mulder, E.G., 1950. *Ann. Rev. Plant Physiol.*, 1: 1–24.

Mulder, E.G. and Gerretsen, F.C. 1952. *Adv. Agron.*, 4: 221–303.

Nicholas, D.J.D., 1961. *Ann. Rev. Plant Physiol.*, 12: 63–90.

Nishita, H., Kowalewsky, B.W. and Larson, K.H., 1956a. *Soil Sci.*, 82: 307–318.

Nishita, H. Kowalewsky, B.W. and Larson, K.H., 1956b. *Soil Sci.*, 82: 401–407.

Pearson, R.W. and Simonson, R.W., 1939. *Soil Sci. Soc. Am., Proc.*, 4: 162–167.

Randhawa, N.S., and Broadbent, F.E., 1965. *Soil Sci.*, 99: 295–300.

Reitemeier, R.F., 1951. *Adv. Agron.*, 3: 113–164.

Rhoades, H.F., 1939. *Neb. Agric. Exper. Stn. Res. Bull.*, 113: 1–23.

Russell, E.W., 1961. *Soil Conditions and Plant Growth.*. Longmans Green, London, 9th ed., 688 pp.

Russell, E.W., 1966. In: *The Use of Isotopes in Soil Organic Matter Studies.* Pergamon, New York, N.Y. pp.3–19.

Sauerbeck, D. and Führ., 1966. In: *The Use of Isotopen in Soil Organic Matter Studies.* Pergamon, New York, N.Y., pp. 61–72.

Schnitzer, M. and Skinner, S.I.M., 1963. *Soil Sci.*, 96: 86–93.

Stanford, G. and Pierre, W.H., 1953. In: *Soil and Fertilizer Phosphorus in Crop Nutrition.* Academic Press, New York, N.Y., pp. 243–280.

Starkey, R.L., 1950. *Soil Sci.*, 70: 55–65.

Starkey, R.L., 1955. *Soil Sci.*, 79: 1–14.

Starkey, R.L., 1956. *Ind. Eng. Chem.*, 48: 1429–1437.

Tisdale, S.L. and Nelson, W.L., 1966. *Soil Fertility and Fertilizers.* Macmillan, New York, N.Y., 2nd ed., 694 pp.

Van Diest, A. and Black, C.A., 1959a. *Soil Sci.*, 87: 100–104.

Van Diest, A. and Black, C.A., 1959b. *Soil Sci.*, 87: 145–154.

Wallace, A., 1965. *Agric. Sci. Rev.*, 3: 18–24.

Whitehead, D.C., 1963. *Soils Fert.*, 26: 217–223.

Whitehead, D.C., 1964. *Soils Fert.*, 27: 1–8.

Chapter 15

AN ION EXCHANGE MATERIAL, CHELATING AGENT, AND BUFFER

INTRODUCTION

In the preceding chapter frequent reference was made to the role played by soil organic matter as a cation exchange material, and to its ability to chelate nutrients. It is also an excellent buffer. Since these properties account for many of the most important benefits derived from its presence in soil it is well to consider at some length just what is meant by these terms, and how and to what extent humus functions in these processes. Since plant roots also possess cation exchange capacities that in many respects resemble those of soil organic matter, reference will also be made to this phase of ion exchange.

ION EXCHANGE IN SOILS

The organic and mineral portions of soils have the ability to adsorb both cations and anions from the soil solution. They may also release these ions to the plant root, or one kind of ion may replace another when conditions, such as ion concentration or pH, change. Numerous references are made in the literature to cation exchange and to cation exchange capacity of a soil, but anion exchange is referred to only occasionally. This is because cation exchange is of far greater importance than anion exchange in soil and plant studies, and much more is known about it. Cation exchange may involve most of the cations that are found in soils, whereas only a very few anions are adsorbed with sufficient strength to make this a major factor in soil productivity.

Cation exchange

Cation exchange was first observed more than a century ago when it was noted that when a dilute solution of ammonium sulfate was added to a soil the leachate first contained calcium sulfate, rather than ammonium sulfate. When potassium sulfate was similarly added, the percolate also contained calcium sulfate initially and not potassium sulfate. In either case the cation in the added solution replaces the calcium of the soil. Not until most of the readily exchangeable soil calcium has been leached out does the added salt appear in the percolate in appreciable amounts.

The seat of most of the ion exchange is in the finer portions of the soil which includes the organic and inorganic colloidal fractions, the clay, and at least the smaller silt particles (Hosking, 1948). This involves the particles having a diameter of about 0.02 mm or less, of which the colloidal portion of less than 0.001 mm plays the major role.

In the natural process of soil formation the finer particles acquire a negative charge which is neutralized by cations that are attracted to the negative surfaces. These cations that are held with varying degrees of tenacity are subject to replacement by other cations and to removal by crops. The development of the initial negative charge on mineral colloids may result from replacement of one atom by another of lower charge, or may follow the formation of hydrogen ions on mineral surfaces. The charge that develops on 2:1 clays is greater than on 1:1 clays (see Tisdale and Nelson, 1966, for an excellent discussion of these processes).

There is considerable uncertainty as to the explanation for the development of the negative charge on organic colloids. It is known, however, that charges arise from the presence of carboxyl, phenolic hydroxyl, enolic hydroxyl, imide, and possibly other groups (Broadbent and Bradford, 1952; Broadbent, 1953; and Mortensen, 1963).

The cation exchange capacities attributed to clays are generally believed to involve two types of charge, namely the so-called "permanent" and the "pH-dependent" charges. The permanent charge is due chiefly to the substitution of ions within the lattice of clay minerals, which results in an excess of negative charges within the lattice that are balanced by cations at the surface. The pH-dependent cation exchange capacity is weakly acidic, increasing with pH. Rich and Thomas (1960) state that "the ionization of these weakly acidic H^+ ions can be compared with that of a weak organic acid, such as acetic acid. In general, the pH of maximum cation exchange capacity can be found near pH 10." There is still much uncertainty as to the reason for the pH dependent charge.

The term cation exchange capacity (CEC) is one that is used very extensively in soils literature. It is defined very simply as the maximum number of adsorbed ions held per 100 g of dry soil (or plant) material (Stout and Overstreet, 1950). In terms of quantity, the principal exchangeable cations in soils are calcium, magnesium, potassium, sodium, hydrogen and aluminum. These ions are held by colloids with different binding energies, calcium being the most tightly held and potassium the least.

The determination of CEC is commonly made by leaching a soil with a neutral barium acetate solution. It may also be made by extracting a soil with normal ammonium acetate solution, followed by normal potassium chloride. The ammonium removed by the potassium chloride is a measure of the CEC of the soil, which includes the cations held by both the organic and inorganic portions. Separate determinations of these portions can be made but less accurately because the separation of one from the other cannot be made without affecting the chemical nature of the organic colloid.

Any important variation in the method of determination of CEC, such as a change in pH or of extracting solution, is likely to affect markedly the value obtained. This is illustrated by the data in Table 15.I, taken from the paper by Broadbent (1955). These data show that divalent copper, which forms stable complexes readily, was retained to a much greater extent than was barium at the same pH value. It is now more or less standard practice to determine CEC at a pH of 7 but if, instead, the determination is made at higher pH values the CEC may be much higher. It is these facts that led Broad-

TABLE 15.I

CATION-RETENTION CAPACITIES OF SOME SOIL ORGANIC MATTER PREPARATIONS AS DETERMINED WITH DIFFERENT LEACHING SOLUTIONS (from BROADBENT, 1955)

Source of organic matter	*Cation retained with leaching solution (mequiv. per 100 g)*			
	barium hydroxide	*copper acetate pH 5*	*barium acetate pH 5*	*potassium acetate pH 5*
Pine forest soil	533	410	155	139
Honeoye silt loam	295	306	146	60
Ontario silt loam	309	278	125	54
Yates silt loam	301	278	124	43
Dunkirk silty clay loam	275	270	135	64
Sequoia forest soil	286	181	118	42

bent to conclude rightly that "the term 'cation-exchange capacity' as applied to soil organic matter would appear to have no meaning unless the conditions of determination are specified."

The relative contributions of organic matter and clay to total CEC was determined on 60 Wisconsin soils by Helling et al. (1964). As the pH of the buffered saturating solution was increased, the average CEC of the organic matter increased gradually from 36 mequiv. per 100 g soil at pH 2.5 to 213 mequiv. at pH 8; the corresponding increase for the clay was from 38 to 64 mequiv. Regression equations indicated that the mean relative contribution of organic matter to total CEC varied from 19% at pH 2.5 to 45% at pH 8.0.

The CEC of a soil is not only determined by the amount of humus and finely-divided inorganic material present but also by the kind of clay present. Grim (1953) states that the CEC of different clays is approximately 3–15 for kaolinite, 10–40 for illite, 100–150 for vermiculite, and 80–150 for montmorillonite. The corresponding values for humus, according to Van Dijk (1966), are likely to be in the range of 150–300; in Coastal Plain soils, Kamprath and Welch (1962) observed values in the range of 62–279 mequiv. for the soil organic matter. Others have reported values as high as 360 mequiv. The more thoroughly the organic matter becomes humified the higher is the exchange capacity. These data show that in many soils a given weight of colloidal humus can contribute several times as much to the CEC value as a like weight of inorganic colloid. In very sandy soils, or in peats and mucks, much more than half of the CEC is likely to be contributed by organic matter. Even in soils intermediate between these two extremes it is not unusual to find that humus is responsible for 30–60% of the CEC.

In studies with typical soils of Puerto Rico, Abruna-Rodriguez and Vicente-Chandler (1955) found that the exchange capacity of the organic matter was usually between 100 and 150 mequiv. per 100 g and accounted for about 25% of the total exchange capacity. The organic matter removed by flotation had the highest exchange capacity. Much of the organic matter was very resistant to oxidation and had a low exchange capacity, which suggested to the authors a close association between the organic matter and the inorganic soil colloids.

The percentage of the CEC contributed by soil organic matter usually decreases with depth in the profile because the proportion of organic matter to clay decreases. This is well illustrated by the data of Broadbent (1955) shown here in Table 15.II. In these two medium-textured gray-brown podzolic soils about half of the CEC in the surface layer was contributed by the organic matter; below a foot in depth the organic matter was responsible for slightly more than a fourth of the CEC. In chernozem soils, where organic matter content is comparatively high at all depths its contribution to CEC would be proportionately greater. Broadbent (1953) cites data showing that even in Maryland soils 50–80% of the CEC is contributed by the organic fraction. A podzolic soil from the Tropics that contained 21.8% organic matter had a CEC value of 50, of which 87% was due to organic matter. Values for Illinois soils were much lower, ranging between 7 and 43%.

The CEC of mineral soils may vary over the range of 2–50 mequiv. per 100 g but it is usually considered that the value should be at least 3–4 mequiv. Values lower than this might occur in very sandy soils but such soils would likely not be suitable for general agricultural use.

McGeorge (1930, 1931) was one of the earlier workers who studied the cation exchange properties of soils. Much of the emphasis in this work was on the exchange properties of lignin and related products since at that time it was generally believed that humus was a lignin complex. He observed that cation exchange in organic soils takes place in chemically equivalent proportions, and that if organic matter is destroyed the loss in

TABLE 15.II.

DISTRIBUTION OF CATION-EXCHANGE CAPACITY WITH DEPTH IN THE ORGANIC FRACTION OF TWO PROFILES (from BROADBENT, 1955)

Horizon	*Depth (inches)*	*Organic matter (%)*	*CEC (mequiv./ 100 g)*	*Exchange capacity due to organic matter (mequiv./100 g)*	*% of total capacity due to organic matter*
Honeoye silt loam					
A_1	0– 2.5	7.30	27.1	13.5	50
A_{22}	5–12	3.88	13.8	7.0	51
B_{21}	12–16	1.48	15.7	4.5	29
B_{22}	16–20	1.88	17.3	6.0	35
B_3	20–25	1.61	14.3	3.1	22
C_2	29+	1.39	9.6	2.2	23
Yates silt loam					
A_1	0–2.5	4.22	12.5	6.2	50
A_{21}	2.5–7	1.46	7.3	2.3	31
A_{22}	7–14	0.47	5.8	0.7	12
B_2	14–20	1.25	8.1	3.4	42
B_3	20–30	1.10	9.4	1.9	21
C_2	30+	0.85	5.1	1.3	26

exchange capacity is approximately a linear function of the amount of organic matter destroyed. Lignin from corn cobs, soil humus, and synthetic humus showed chemically equivalent exchange capacity. Exchange capacity of organic matter increased as the organic matter passed through successive stages of decomposition in the soil.

Calcium is usually the principal exchangeable cation found in soils, and there is considerable evidence that unless the exchange complex has a degree of saturation with calcium of 30–35% there is likely to be an inadequate uptake of this element, followed by reduced plant growth (Stout and Overstreet, 1950). It was previously pointed out that there are close interrelations between calcium, magnesium and potassium, and that a proper balance among these elements on the exchange complex is also very essential for optimum plant growth.

Anion exchange

Soils possess anion exchange capacities for certain anions that increase as the pH decreases. This property of anion exchange has been shown to be greatest in soils that consist largely of 1:1 clay minerals and hydrous oxides of iron and aluminum; the 2:1 clays have a lower anion-retaining capacity.

The chief nutrient anions in soil are NO_3^-, SO_4^{2-}, Cl^- and $H_2PO_4^-$. The phosphate anion is held so strongly in the exchange complex that plants can obtain it only with difficulty. Soils may be well supplied with this fixed phosphate but yet require large amounts of phosphate fertilizer for optimum growth. In contrast, nitrate and chloride ions are not fixed but are easily extracted with water. Sulfate ions are held to only a very slightly greater extent than are nitrate and chloride. Except for phosphate, anion exchange is not a very important factor in agricultural soils.

There is no evidence that organic matter has sufficient anion retention capacity for it to play an important role in holding these nutrients by this mechanism. Both phosphorus and sulfur are held in the organic colloids as constituents of organic molecules but not in exchangeable forms.

CATION EXCHANGE IN ROOTS

Roots have cation exchange properties that correspond closely to those exhibited by soils. They are believed to act as amphoteric colloids and absorb cations from the plant culture solution or soil. Cations are held by the roots when they are placed in water but may be set free when other cations are added to the culture medium. They are also readily removed by electrodialysis, and this serves as a convenient way of measuring root CEC. The accuracy of this method has been questioned because of the uncertainty as to whether this procedure removes all of the exchangeable cations, and only these. Furthermore, some organic substances may also be removed, leaving hydrogen ions adsorbed on the root surface.

The CEC of roots, as determined by various workers, has ranged from about 12 to 71 mequiv. per 100 g of dry roots. The values for legumes usually fall in the upper half of this range and those for the grasses in the lower half (Brown, 1963). This corresponds to the well-known fact that legumes are high in calcium and other bases but the ash of grasses is much lower in total bases, and those present are largely monovalent cations. This agreement may be wholly fortuitous, however, for root cation exchange involves surface adsorption rather than internal composition.

There is little agreement among workers as to the significance or importance of root CEC in plant nutrition. In the absence of direct positive information that this CEC is important there has been a tendency to belittle this property, at least until facts to the contrary are published. Brown (1963) seems to have drawn a logical conclusion, namely, that "too much evidence exists showing interactions involving soil colloids, cation exchange in roots, and nutrient elements to dismiss the cation exchange capacity of roots as having no influence on the nutrient status of plants".

CHELATION OF METALS

Much emphasis has been placed in recent years on the use of chelates in supplying plants with iron, zinc, copper and manganese. Since chelation reactions are believed to be involved in the reaction of humus with these metal ions it is appropriate to consider what is meant by chelation and to compare the status of metals held in this manner with that of those held in the organic matter exchange complex. Incidentally, the formation of soluble metal–organic complexes has long been known although emphasized only comparatively recently (Horner et al., 1934).

The word chelate is derived from the Greek word chele (claw). One or more organic compounds may act as the claw to surround and bind the metallic element. Chelation has been defined by Lehman (1963) as "the equilibrium reaction between a metal ion and a complexing agent, characterized by the formation of more than one bond between the metal and a molecule of the complexing agent and resulting in the formation of a ring structure incorporating the metal ion." Metal chelates are water soluble and the metals are held at varying degrees of stability. The stability is usually high, but is determined largely by the number of atoms that form a ring with the cation, the number of participating rings, the nature of the ligands and the presence or absence of certain substituents in the chelate (Van Dijk, 1966). The principles of chelation chemistry and main factors involved are discussed by Lehman (1963), Martell (1957) and Burström (1963).

The great importance of chelation in nature has been stressed by Schatz (1963), and also in several other articles by the same author. In one of these the opinion is expressed that "since the chelating ability of organic matter may be its most important property and function, the relatively neglected metal chelates may turn out to be the most important constituents of soils." This statement may be a little optimistic but there is no doubt that one of the main benefits derived from the presence of organic matter in soils is through organo-metallic interactions. There is much evidence that rock weathering is largely brought about by the action of living organisms (Jacks, 1953), and this same process continues in the disintegrated rock and soil. Lichens, moss, algae, diatoms, bacteria and fungi are all active weathering agents. Some of the weathering may be attributed to the acids that they produce, but more recent studies indicate that chelation reactions are far more important.

Studies made by Duff et al. (1963) show that certain bacteria can produce 2-ketogluconic acid that chelates with some metals. About 17% of the phosphate released from dicalcium phosphate in the presence of these bacteria was in the form of organic phosphate. There was also some release of silica from silicates. These authors give a good summary of present information dealing with the process of solubilization of insoluble materials in nature. They point out the important role of microorganisms in these processes. The acids known to be formed by them in addition to 2-ketogluconic, include acetic, formic, butyric, citric, lactic, succinic, glycollic, gluconic and galacturonic. There seems to be no doubt that the carbohydrate acids act as effective chelating agents, and these are of course formed from soil organic matter when in the active stage of decomposition.

Several synthetic chelating agents are being used in agriculture for the correction of deficiencies of one or more of the four metallic elements mentioned above. These include ethylenediaminetraacetic acid (EDTA), ethylenediamine di(*o*-hydroxyphenylacetic acid) (EDDHA), diethylenetriaminepentaacetic acid (DTPA), hydroxyethylethylenediaminetriacetic acid (HEDTA), and nitrilotriacetic acid (NTA). (Wallace, 1960, 1963a, b, 1965; Haertl, 1963; Brown, 1969).

Many chemicals have been tested for chelating ability but only a few of these have been found satisfactory for practical use. Most naturally-occurring compounds are decomposed by microorganisms so readily that they are unsatisfactory for application to soils, but may be used as foliar sprays. According to Wallace (1965) a metal chelate suitable for use in soils should be: (1) resistant to microbial decomposition; (2) water soluble; (3) specific for the metal; (4) stable against hydrolysis and other means of inactivation; and (5) supply the metal in a form available to the plant either at the plant root or within the plant sap after absorption. Wallace et al. (1957) discuss the reactions of chelates in soils and plants, and the comparative merits of soil and spray applications.

Iron deficiency is more difficult to correct than deficiencies of either zinc, copper, or manganese. On calcareous soils where iron deficiency is most likely to be encountered the iron chelate of EDDHA has been used with marked success. Its wider general use has been limited by the cost of the material. EDTA, which is less expensive, is often used to supply iron on acid and neutral soils but it undergoes hydrolysis with the formation of iron hydroxide when applied to alkaline soils. Synthetic chelates are also used to a limited extent to supply the other minor elements mentioned above (Benson et al., 1957) but on large acreages this is seldom practical; it is usually satisfactory to supply these as salts or minerals in the fertilizer. Thorough mixing with the soil greatly increases the effectiveness of these nonchelated metals. Likewise, an abundant supply of soil organic matter will often make the use of synthetic chelates unnecessary.

Problems are sometimes encountered in the use of chelates due to the chelate metal being replaced by other metals in the soil. Sometimes calcium interferes with the utilization of zinc chelates, but this is seldom a major problem because zinc chelates are many times more stable against hydrolysis than are calcium chelates.

Chelating agents without metals, and supplied as acids or sodium salts, may sequester the heavy metals from comparatively insoluble forms present in soil. This is generally not a good method of correcting micronutrient deficiencies because these agents compete with plant roots. In occasional cases the chelating agent may make soluble so much of the insoluble metal in the soil that toxicity results.

The mechanisms by which the chelates enter plants are not well understood. The chelating substances keep the metals soluble in the soil and are usually taken up by plants with the metals (Holmes and Brown, 1955). In some cases both the metal and chelate are absorbed in corresponding amounts but often the two components are separated in the roots, and the metal enters without the equivalent amount of the carrier. There is also evidence that some of the benefits derived from chelating agents are the result of increased translocation of the metal from the roots to the shoots. Many factors, such as pH, plant species, and metal involved affect the process. In fact, some plants do not respond to additions of chelate metals and the reasons are still in doubt.

One of the important benefits of chelates, other than supplying metals, is realized as a result of their improvement of the micronutrient balance of plants. For example, Holmes and Brown (1955), in studies with calcareous soils, observed that certain effective chelates increased the concentration of iron in soybeans, and at the same time decreased the concentration of manganese and copper. This suggests that the cause of iron-deficiency chlorosis in this case may have been improper microelement balance in these calcareous soils. These workers also observed that when chelate was applied to several soils, it alleviated iron chlorosis completely in some soils, partly in others, and caused toxicity in yet others. From the work of others we know that under other conditions chelates may also eliminate or greatly decrease toxic effects where heavy metals are present in excessive amounts. Numerous soil factors influence these varying responses.

RETENTION OF METALS BY SOIL ORGANIC MATTER

In the above discussion reference was first made to cation exchange and later to chelation, and the two terms were defined. Very simply stated, cation exchange is the process by which metallic ions are exchanged between the solid portion of the soil and the liquid that surrounds it. The emphasis here is on the properties of being exchangeable and reversible. Likewise, in simple terms a metal chelate is the complex formed when a metal ion is bound to an organic component by more than one bond to form a ring or cyclic structure. It is now established, or at least generally agreed, that soil organic matter can hold metallic elements both by cation exchange and by chelation. Although chelated metals are usually held rather tenaciously by the organic component, this is not always the case. The result is that with our present limited knowledge of metallo-organic interactions it is often not possible to know whether a metal is held by a true exchange mechanism or by chelation. This is especially true in the case of metals held by large organic complexes of uncertain chemical composition, such as humus. Cation exchange and chelation in soils will, therefore, be discussed together.

Mortensen (1963) states that organic matter forms complexes with metals by several mechanisms, including ion-exchange, surface adsorption, chelation, and complex coagulation and peptization reactions. He considers it probable that the ligands in polymeric components of soil organic matter involved in chelation include carboxyl, hydroxyl, and amide groups, although conclusive proof of this has not been offered. The ligands may be present in polymers or mixtures of polymers of lignin, polysaccharides, tannins, and other polyphenols, proteins, and quinones. He points out that a number of low molecular weight compounds that could act as chelating agents have been isolated from soil organic matter. These include amino acids, organic phosphates, aliphatic acids and phenolics. He presents a rather complete review of recent research on the complexing of metals by soil organic matter.

This matter of size of organic molecule is an important factor in determining how a metal is held. Very large organic complexes can obviously adsorb, or chemically bind a metallic ion in a readily exchangeable state, whereas such a complex might not be able to form a ring structure around the metal. The commercial chelates are not large complexes but comparatively small molecules that can readily incorporate a metal inside a ring structure. Numerous low molecular weight compounds capable of chelating metals have been isolated from soils but the bulk of soil organic matter seems to be in stable complexes. Lewis and Broadbent (1961b) state that the chemistry of functional groupings attached to large molecules, as in soil organic matter, is usually similar to that of much simpler systems. Van Dijk (1966), however, questions the ability of these substances to bring about strong chelation, largely because of sterical hindrance.

The present concept of the nature of humus as presented by Swaby and Ladd (1962), Whitehead and Tinsley (1963), Flaig (1966), and others is that it is a large spherical, amorphous, phenolic-amino acid, cross-linked polymer, possibly with inorganic elements or oxides bound in the complex. There is little reason to doubt that this description of humus is essentially correct although future research may require some modifications of this concept. If we grant this, then it is a little difficult to conceive of it forming chelates with metals, since chelates are commonly described as water-soluble. It is probable that surface groups on such a large polymer might bind metals but the reaction products would scarcely conform to our present definition of a chelate. Such a molecule with active surface groups would, however, seem to provide an ideal structure for holding and releasing metal ions; in other words it would provide high CEC, as we know it does. Organic matter is of course not all present as large molecules; much of it is in simple units undergoing synthesis to the larger molecules or present as breakdown products of humus. Many of these small molecules are capable of very effective chelation.

De Silva and Toth (1964) studied colloidal clay soils of kaolinite, bentonite and illite and observed no isoelectric point; the soils remained electronegative over a wide range of pH. In similar studies, organic colloids from high-moor peat and coal humus were also electronegative but those from alfalfa compost and wheat straw composts were amphoteric. Titration curves of these organic colloids showed several stepwise inflection points which were probably related to the dissociation of H ions from different functional groups. It is of much interest to note that during the preparation of clay–organic complexes a reduction in CEC of both the clays and the organic colloids occurred that ranged from 18–90 % over a pH range of 5.5–8.5. This may help to explain why plants tend to form masses of small rootlets wherever a mass of decaying organic matter occurs in soils. The humus, apart from clays, is doubtless an abundant source of available nutrients held as exchangeable ions on the colloid.

If the matter of water solubility is ignored it would seem that humic acid might well form many multiple bonds with di- and trivalent metals. These metals would be truly chelated in the sense that they would not be readily released, but the complex would usually not be soluble. This is probably what happens to copper when added to peat soil.

In the early stages of decomposition of plant and animal substances many simple substances are formed that can readily react as chelating materials. Many, or most, of the reaction products would be water soluble but probably rather transitory since they would be subject to further biological attack.

The formation of a typical podzolic profile is now considered to be dependent to a large extent on chelation reactions (Atkinson and Wright, 1957). Wright and Schnitzer (1963) demonstrated this very clearly by leaching a calcareous parent material with the chelating agent EDTA for 9 hours per day for 17 months. The profile produced resembled that of a podzolic soil and had distinct bands resembling A_2- and B-horizons. According to their explanation, the calcium and magnesium moved downward probably both as ions and as chelates. As the pH and concentration of alkaline earth metals in solution at the top of the column decreased, more iron and aluminum were chelated and moved downward. At lower depths with rising pH and greater concentration of alkaline earths some of the iron and aluminum were precipitated as hydrated oxides.

Under natural conditions, Wright and Schnitzer (1963) consider that fulvic acid is the chief ligand bringing about the movement of iron and aluminum in podzol development. Their studies indicate that fulvic acid consists of an aromatic "nucleus" to which carboxyls, hydroxyls and carbonyls are attached as functional groups. The fulvic acid probably chelates with iron and aluminum, etc., as it moves downward, and at lower levels precipitation occurs. This ability of fractions of soil organic matter to make iron mobile probably accounts for the fact that plants can obtain their required amounts even though the soil iron is present only in very insoluble forms.

The factors that are involved in the reaction of metal ions with soil organic matter, the organic groups involved, and the stability and activity of the complexes have been studied by Broadbent (1957), Broadbent and Ott (1957), Himes and Barber (1957), Miller and Ohlrogge (1958), Lewis and Broadbent (1961a, b), Randhawa and Broadbent (1965a,b), Khanna and Stevenson (1962), Schnitzer and Skinner (1963a,b; 1964; 1965). These studies, which cannot be discussed in detail here, would seem to leave little doubt that chelation reactions in soil organic matter are very important in making metal ions available and in holding them in forms such that plants have a supply as needed.

SOIL AS A BUFFER

A buffer solution is defined by Webster's *Dictionary* as a "solution that usually contains on the one hand either a weak acid (as carbonic acid) together with one of the salts of this acid or at least one acid salt of a weak acid or on the other hand a weak base (as ammonia) together with one of the salts of the base and that by its resistance to changes in hydrogen-ion concentration on the addition of acid or base is useful in many chemical, biological, and technical processes."

Weak acids other than carbonic that, together with their salts, are used as buffers include acetic and boric acids. The sodium and potassium salts of phosphoric acid, namely mono- and di-potassium (or sodium) phosphate are also very commonly used buffers in the laboratory and greenhouse. Neither strongly dissociated acids, such as hydrochloric, nitric and sulfuric, nor strongly dissociated bases, such as sodium and potassium, act as buffers. Stated another way, it is the acids that have low active acidity but high potential acidity that are suitable for use as buffers. Likewise, the bases must have low active basicity and high potential basicity.

Soils behave very much as do the buffer mixtures described above. Most of their buffering capacity is in the colloidal humus and clays which hold hydrogen, aluminum and other cations. If an acid soil is suspended in water and titrated with an alkali it will be observed that a much larger quantity of the base is needed to bring the pH to the neutral point than if a water solution of the same initial pH, containing a strong acid but not soil, is titrated to neutrality. In a similar manner, a neutral soil will resist a pH change to lower levels when an acid is added. This resistance to pH change is limited in very sandy soils but very strong in fine-textured soils and in organic soils. These are the ones that have high CEC values. In soils that are high in insoluble bases, such as calcium carbonate, the resistance to pH change on the addition of a strong acid is obviously the result of neutralization of the base first, and CEC second.

Russell (1966) offers a possible and plausible explanation for the evenly-buffered status of humus over the range of pH values commonly found in agricultural soils. He states that the negative charge of humus is "due in part to the dissociation of hydrogen ions from carboxylic acids, and probably in part to their dissociation from phenolic hydroxyls, and particularly from groups of two hydroxyls, which are in the ortho-position with respect to each other on a benzene ring, for such hydroxyls will begin to dissociate hydrogens at about the same pH as the carboxylic acids become fully dissociated."

This buffering capacity of soils is of great practical importance. If it did not exist it would be difficult to conceive of agriculture as we know it today. We would have a situation similar to that encountered in growing plants in solution cultures (hydroponics). Plants could be grown but only in a limited way and at great expense and attention to detail. Both acids and bases are being produced more or less continuously in field soils and, if there were no buffer present, marked fluctuations in pH would follow. This would kill or injure many plants, since most crops grow well only where the pH remains within a fairly narrow controlled range. The more humus present the better is the soil buffered.

SOME PRACTICAL CONSIDERATIONS

The above discussion has shown that soils have the capacity to adsorb, hold, and release cations, depending upon conditions in the soil, and plant demands. They may also to a lesser extent adsorb and release phosphate anions. Soils may also fix some metals by chelation, sometimes so firmly that they are difficultly available for plants, or in other cases the movement into the plant of the chelated metal is greatly facilitated. Chlorotic plants, for example, when supplied with chelated iron may quickly turn from yellow to dark green and resume their normal rate of growth. In addition, the soil may act as a weak acid and serve as an excellent buffer against changes in pH, which is so essential for plant growth.

These various processes involve, for the most part, chemical reactions and chemical absorption. In addition, it should be mentioned that purely physical adsorption plays an important role in making the soil a suitable environment for plant growth. Both humus and inorganic colloids are the seat of this physical adsorption just as they are of the various chemical reactions discussed above. Even if these colloids lacked cation and anion exchange properties, chelating ability, and buffering capacities, they would still serve a very important and essential role in making the soil a productive one. Probably the most obvious beneficial physical effects are those exerted on water retention, soil structure, aeration, gas adsorption and nutrient retention. Admittedly, these effects may not always be beneficial but under good soil management they need seldom be unfavorable. Certainly, if colloids were largely absent from soils the residue would resemble our dry, unproductive, barren sands or silty sands.

A summation of all of these facts shows that the soil serves as an excellent reservoir of plant nutrients – a reservoir that can be added to or subtracted from, depending on additions made to it in the form of fertilizers and crop residues, and on removals by crops and through leaching. Appreciable changes in inorganic colloids cannot be made but in many instances the organic colloids can be increased, or at least maintained. The nutrients are held rather tightly against leaching, but usually not so tightly that the plants cannot get them as they need them, assuming of course that an adequate supply is present.

Soil colloids, especially humus, can also adsorb gases, such as ammonia and oxides of nitrogen that would escape from a very sandy soil. Even a brief period of retention is usually adequate time for them to be oxidized, or to react to form nongaseous compounds that plants can utilize.

Humus and inorganic colloids also alleviate the effects of excessive amounts of macro- and micro-nutrients. If these colloids were not present it would be extremely difficult to apply some of these nutrients sufficiently uniformly to avoid toxicity. This would apply especially to some of the micronutrients that are very toxic in concentrations as low as a few parts per million. By means of the CEC, or by precipitation as insoluble compounds, the excessive concentration of nutrients, perhaps only in local spots, may be removed from the soil solution and thus inactivated. Humus is particularly effective in this respect because of its very high CEC and adsorptive capacity. In popular language we can say that a goodly supply of humus makes the soil "foolproof" against an oversupply of nutrients. In the absence of soil colloids, if crops could be grown at all, it would be necessary to supply very small amounts of some of the nutrients at frequent intervals throughout the growing season.

The colloidal materials in soil also protect plants against many of the numerous pesticides that are now in common use in agriculture (Mader, 1959). Only rarely do these materials, at the rates commonly used, cause injury to crops. But as the colloid content of soils decreases the possibility of injury increases. Humus is especially effective in protection against insecticide residues that contain copper. It has been shown repeatedly that where pesticides are applied directly to soils the effective dose increases markedly as the colloid content of the soil increases. This shows how effective colloids are in inactivating toxic materials. The literature is covered rather fully by Bailey and White (1964).

Occasionally toxic substances are formed in soils following the turning under of very large amounts of crop residues, or perhaps during a brief period of waterlogging. Colloids aid materially in adsorbing or neutralizing these substances.

REFERENCES

Abruna-Rodriguez, F. and Vicente-Chandler, J., 1955. *J. Agric., Univ. P.R.*, 39: 65–76.

Atkinson, H.J. and Wright, J.R., 1957. *Soil Sci.*, 84: 1–11.

Bailey, G.W. and White, J.L., 1964. *J. Agric. Food Chem.*, 12: 324–332.

Benson, N.R., Batjer, L.P. and Chmelir, I.C., 1957. *Soil Sci.*, 84: 63–75.

Broadbent, F.E., 1953. *Adv. Agron.*, 5: 153–183.

Broadbent, F.E., 1955. *Soil Sci.*, 79: 107–114.

Broadbent, F.E., 1957. *Soil Sci.*, 84: 127–131.

Broadbent, F.E. and Bradford, G.R., 1952. *Soil Sci.*, 74: 447–457.

Broadbent, F.E. and Ott, J.B., 1957. *Soil Sci.*, 83: 419–427.

Brown, J.C., 1963. *Ann. Rev. Plant Physiol.*, 14: 93–106.

Brown, J.C., 1969. *Soil Sci. Soc. Am., Proc.*, 33: 59–61.

Burström, H., 1963. *Adv. Bot. Res. (Swed.)*, 1: 73–100.

De Silva, J.A. and Toth, S.J., 1964. *Soil Sci.*, 97: 63–73.

Duff, R.B., Webley, D.M. and Scott, R.O., 1963. *Soil Sci.*, 95: 105–114.

Flaig, W., 1966. In: *The Use of Isotopes in Soil Organic Matter Studies.* Pergamon, New York, N.Y., pp. 103–127.

Grim, R.E., 1953. *Clay Mineralogy.* McGraw-Hill, New York, N.Y., 384 pp.

Haertl, E.J., 1963. *J. Agric. Food Chem.*, 11: 108–111.

Helling, C.S., Chesters, G. and Corey, R.B., 1964. *Soil Sci. Soc. Am., Proc.*, 28: 517–520.

Himes, F.L. and Barber, S.A., 1957. *Soil Sci. Soc. Am., Proc.*, 21: 368–373.

Holmes, R.S. and Brown, J.C., 1955. *Soil Sci.*, 80: 167–179.
Horner, C.K., Burk, D. and Hoover, S.R., 1934. *Plant Physiol.*, 9: 663–669.
Hosking, J.S., 1948. *J. Counc. Sci. Ind. Res. (Aust.)*, 21: 38–50.
Jacks, G.V., 1953. *Soils Fert.*, 16: 165–167.
Kamprath, E.J. and Welch, C.D., 1962. *Soil Sci. Soc. Am., Proc.*, 26: 263–265.
Khanna, S.S. and Stevenson, F.J., 1962. *Soil Sci.*, 93: 298–305.
Lehman, D.S., 1963. *Soil Sci. Soc. Am., Proc.*, 27: 167–170.
Lewis, T.E. and Broadbent, F.E., 1961a. *Soil Sci.*, 91: 341–348.
Lewis, T.E. and Broadbent, F.E., 1961b. *Soil Sci.*, 91: 393–399.
McGeorge, W.T., 1930. *Ariz. Agric. Exper. Stn., Tech. Bull.*, 30: 182–213.
McGeorge, W.T., 1931. *Ariz. Agric. Exper. Stn., Tech. Bull.*, 31: 215–251.
Mader, D.L. 1959. *Soil Sci. Soc. Am., Proc.*, 23: 252–253.
Martell, A.E., 1957. *Soil Sci.*, 84: 13–26.
Miller, M.H. and Ohlrogge, A.J., 1958. *Soil Sci. Soc. Am., Proc.*, 22: 225–231.
Mortensen, J.L., 1963. *Soil Sci. Soc. Am., Proc.,*, 27: 179–186.
Randhawa, N.S. and Broadbent, F.E., 1965a. *Soil Sci.*, 99: 295–300.
Randhawa, N.S. and Broadbent, F.E., 1965b. *Soil Sci.*, 99: 362–366.
Rich, C.I. and Thomas, G.W., 1960. *Adv. Agron.*, 12: 1–39.
Russell, E.W., 1966. In: *The Use of Isotopes in Soil Organic Matter Studies.* Pergamon, New York, N.Y., pp.3–19.
Schatz, A., 1963. *J. Agric. Food Chem.*, 11: 112–118.
Schnitzer, M. and Skinner, S.I.M., 1963a. *Soil Sci.*, 96: 86–93.
Schnitzer, M. and Skinner, S.I.M., 1963b. *Soil Sci.*, 96: 181–186.
Schnitzer, M. and Skinner, S.I.M., 1964. *Soil Sci.*, 98: 197–203
Schnitzer, M. and Skinner, S.I.M., 1965. *Soil Sci.*, 99: 278–284.
Stout, P.R. and Overstreet, R., 1950. *Ann. Rev. Plant Physiol.*, 1: 305–342.
Swaby, R.J. and Ladd, J.N., 1962. *Trans. Int. Meet. Comm. IV and V, Int. Soil Sci. Soc., N.Z.*, pp. 197–202.
Tisdale, S.L. and Nelson, W.L., 1966. *Soil Fertility and Fertilizers.*. Macmillan, New York, N.Y., 2nd ed., 694 pp.
Van Dijk, H., 1966. In: *The Use of Isotopes in Soil Organic Matter Studies.* Pergamon, New York, N.Y., pp.129–141.
Wallace, A., Shannon, L.M., Lunt, O.R. and Impey, R.L., 1957. *Soil Sci.*, 84: 27–41.
Wallace, A., 1960. *Ann. N.Y. Acad. Sci.*, 88: 361–377.
Wallace, A., 1963a. *Soil Sci. Soc. Am., Proc.*, 27: 176–179.
Wallace, A., 1963b. *J. Agric. Food Chem.*, 11: 103–107.
Wallace, A., 1965. *Agric. Sci. Rev.*, 3: 18–24.
Whitehead, D.C. and Tinsley, J., 1963. *J. Sci. Food Agric.*, 14: 849–857.
Wright, J.R. and Schnitzer, M., 1963. *Soil Sci. Soc. Am., Proc.*, 27: 171–176.

Chapter 16

A FACTOR IN SOIL AGGREGATION AND ROOT DEVELOPMENT

INTRODUCTION

Soil organic matter is responsible to a very great extent, directly or indirectly, for making the physical environment of soils suitable for the growth of crops. It exerts this benefit largely through its effect on soil aggregation which in turn influences soil incrustation, water infiltration, moisture content, drainage, tilth, aeration, temperature, microbial activities, and root penetration.

Much research has been done in attempts to clarify the mechanisms by which some kinds of organic matter exert major effects on soil aggregation, whereas other kinds have negligible effects. Most of these studies have three shortcomings: (1) all agricultural soils have organic matter present and hence there is no zero organic matter control; (2) studies are necessarily conducted for only a comparatively short time; and (3) aggregation has usually been measured by the wet-sieve method which often gives unsatisfactory, or even misleading results.

With regard to the first of these shortcomings, discussed in Chapter 9, all normal surface soils have organic matter so intimately bound to, or mixed with, the clay fraction that it cannot be separated completely from the inorganic portion without bringing about changes in the organic or inorganic portions, or both. If not removed, this initial organic matter may affect seriously any experimental results obtained. In attempts to avoid this difficulty, much research has been done with deep subsoils that are almost free of organic matter, or with "pure clays" from mines. This practice has yielded some very fine data that supplement other results obtained with normal soils, but there is necessarily considerable doubt as to how applicable such results are to agricultural soils. Soils commonly consist of mixtures of different kinds of clay minerals of various textures and widely varying chemical composition and physical make-up. The presence in soils of such substances as iron and aluminum oxides and hydroxides, calcium carbonate, and various other inorganic constituents doubtless serves to modify the behavior of added organic matter with respect to its effect on the physical properties of the soil.

The second shortcoming of research on soil aggregation concerns the importance of time. There is much evidence that the mechanisms of aggregation and stabilization, particularly the latter, are often very different in a one-month laboratory experiment, or in a one-season field experiment, than in soils left undisturbed for many years. Recently-formed aggregates are likely to be only moderately stable, whereas old aggregates are usually more firmly cemented and longer lasting. Microscopic studies of thin sections of field soils serve to emphasize very strongly what long-continued leaching, weathering, deposition and root action can do to a soil profile. Such studies make one question the practical application of many short-time studies with "pure clays" conducted under laboratory or greenhouse conditions.

The third shortcoming centers around the need for a good method for the determination of stable aggregates. The wet-sieve method, now commonly used, is generally recognized to be far from satisfactory. This is illustrated by the experiments of Harris et al. (1963), discussed below and shown in Fig.16.1. If a method had been used that measured true stable aggregates, as occur in nature, the values obtained would doubtless have been zero, or near zero, instead of values ranging up to 100%.

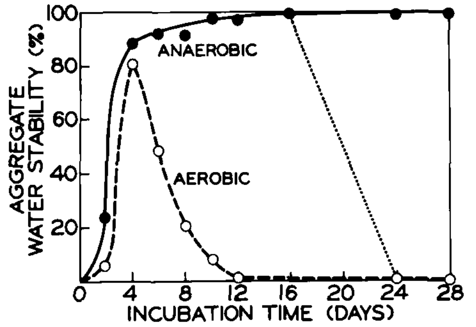

Fig.16.1 Effect of aerobic and anaerobic incubation on the water stabilities of sucrose-amended Waupun soil aggregates. (Redrawn from Harris et al.,1963.)

As a result of the difficulties of experimentation, and the fact that the soil is a very complex and changing medium, our knowledge of soil aggregate formation and stabilization is rather inexact. Many theories and hypotheses have been advanced but positive proof of most of these is still lacking. An attempt is made here to present the major findings and interpretations that seem to meet with general agreement, together with a few of my own suggestions. Reference should be made to papers by Russell (1938), Stallings (1952), Page (1954), Martin et al. (1955), Harris et al. (1966), and Allison (1968) for more complete coverage of the subject.

SOIL AGGREGATION

The terms "soil aggregation" and "soil structure" are sometimes used interchangeably. This is, strictly speaking, incorrect. Martin et al. (1955) define a soil aggregate as a "naturally occurring cluster or group of soil particles in which the forces holding the particles together are much stronger than the forces between adjacent aggregates." Marshall (1962) defines soil structure as "the arrangement of the soil particles and of the pore space between them. It includes the size, shape, and arrangement of the aggregates formed when primary particles are clustered together into larger separable units." According to this definition a soil has structure even if no aggregates are present.

Most of the physical effects that organic matter exerts in soils are realized through the formation and stabilization of aggregates as defined by Martin et al. The emphasis here is on very stable aggregates, not only stable against water but at least fairly resistant to mechanical disturbance and other changes in soils with time. The degree of stability also affects structure, as defined by Marshall, but in the discussion that follows the emphasis is on aggregation.

Aggregate formation and stabilization are often discussed together but the writer prefers to consider them separately. By doing so the point is emphasized that the two processes are for the most part distinct one from the other, although often occurring simultaneously. Sometimes the forces responsible for aggregate formation also help to hold the newly-arranged particles in position, but usually these forces alone are inadequate for long-time stability. It is also true that some of the best stabilizing agents have little or no effect on the formation of aggregates.

Aggregate formation involves primarily the orientation of the finer soil particles and bringing them so close together that the physical forces hold them firmly when allowed to dry. The chief factors involved are particle size, wetting and drying, freezing and thawing and other temperature changes, cultivation, plant growth and possibly microorganisms and earthworms. Chemical and electrical forces may also be involved in at least a minor way.

In aggregate stabilization we are by definition (Martin et al. 1955) concerned with both the forces and conditions that exist within the aggregate, and with those that exist on the outside. The former are so much more important that the latter are often ignored.

Inside the aggregate the forces must be sufficiently strong to hold the soil particles together as highly stable aggregates. This is accomplished by microbial gums and various low molecular weight humic substances, as well as by numerous inorganic substances. These substances stabilize aggregates formed by various mechanisms but have little ability to form stable aggregates. The physical attraction between clay particles is a very important factor.

Outside the aggregate it is also important that the forces be weaker than those inside to insure the formation of small stable aggregates rather than massive clods. Any agent or substance outside of aggregates that keeps them separated would tend to keep the individual aggregates intact. Materials such as peat, large spherical humus molecules, exfoliated vermiculite, and other comparatively inert materials that act as diluents will accomplish this. Growing plant roots that are instrumental in aggregate formation can also keep aggregates small and separated. This is accomplished largely through frequent changes in the forces around the root and surrounding clay particles.

Most studies of aggregate formation, as already stated, have been made with surface soils that contain considerable organic matter and other stabilizing substances. This fact should be kept in mind continually in considering the discussion of aggregate formation that follows. Undoubtedly the presence of these stabilizing substances does under some conditions affect aggregate formation.

Factors involved in aggregate formation and degradation

When we consider the matter of formation of aggregates we usually think in terms of bringing about cohesion between masses of individual particles to form stable clusters having diameters of < 5 mm. It is well to bear in mind, however, that aggregates of this size can also be formed by the partial disintegration of large masses of tightly cohering particles, commonly designated as clods. Such large masses may be the result of the operation of many factors, such as puddling, mechanical compaction, deficient organic matter, or normal desiccation of a fine-textured soil.

In the present discussion, dealing with the factors involved in aggregate formation, and later with aggregate stabilization, reference will be primarily to synthesis from single grains rather than to the disintegration of clods. This simplifies the discussion, and also covers the phase of the subject of most immediate interest and the least understood.

Particle size

Aggregates may be formed from various mixtures of sand, silt and clay, provided the proportion of clay is large enough to hold the mixture together. The presence of some kinds of organic matter may aid in the process of aggregation but the clay fraction usually plays the principal role when dealing with coarse-textured soils. When the clay content is less than about 10% the soil is likely to behave as though nonaggregated. Where various-sized particles are present the smaller ones tend to fit into the spaces between the larger ones, thereby reducing the pore space and the free movement of both air and water.

Wetting and drying

Experiments involving the wetting and drying of naturally-occurring soil aggregates have shown variable results. The factors involved include the kind of soil, the stability of the aggregate, its air and moisture content, and the extent and degree of wetting and drying. Usually if air-dry aggregates are suddenly immersed in water they are shattered. On the other hand, if the aggregates are allowed to absorb moisture slowly, as from a humid atmosphere, and finally carefully brought up to the equivalent of field capacity, there is likely to be little or no disruption. It has been shown that if dry aggregates are evacuated and wetted, even if rapidly, there is little disintegration. These observations emphasize the dominant role that air entrapment plays in aggregate breakdown. Unless the air is removed from the dry aggregates, as by evacuation, or the wetting process is slow enough to allow it to escape slowly, the aggregate is literally exploded as the air suddenly rushes to the outside. As the temperature increases, disintegration also increases.

When natural soil aggregates are dried in the oven, increased water-stability has been observed. The explanation for this is not fully known but Harris et al. (1966) suggest that a major factor is the irreversible or slowly reversible dehydration of organic or inorganic colloidal substances that may be present. They point out that this would reduce the rate of entry of water and also strengthen the aggregating bonds. Certainly dehydration of any aggregating organic cements should make the cements stick more tightly.

Drying, as it occurs naturally, can also affect the stability of aggregates. In discussing this, Greenland (1965b) states that "drying and perhaps simple ageing of organic materials around clay materials may lead to the formation of films which can only be removed by drastic treatments."

One of the most striking evidences of the effect of wetting and drying is encountered in soils of high clay content, as where clay has been transported by water and deposited at a lower level. When wet, such a clay soil is in an expanded condition but on drying shrinking takes place, leaving cracks that often reach a diameter of an inch or more. As drying takes place, both horizontal and vertical movement of the soil particles occur. The shearing movements produce considerable orientation of the clay which favors the formation of dense masses with minimum air space. Such a dense soil with few desirable size aggregates is likely to be a problem soil with respect to tilth.

These facts show that wetting and drying changes may occasionally favor aggregation, but under field conditions are more likely to destroy aggregates, or at least reduce their size. Destruction of aggregates at or near the soil surface may be marked if rain occurs when the soil is very dry. The sudden escape of air from the aggregates would break them up, and in addition the force involved in raindrop splash would be even more harmful. The crust that forms on exposed soils consists chiefly of disintegrated aggregates that have become bound together again, as always occurs after puddling and drying.

Freezing and thawing

It has been generally assumed that freezing and thawing tend to have a harmful effect on soil aggregation. This is true under many conditions (Logsdail and Webber, 1959) but certainly not under all. The effect of frost on a soil depends on a number of factors, chief of which are soil texture, degree of aggregation, stability of the aggregates, moisture content, percentage of the total moisture that is not frozen, and the rate of freezing.

Slow freezing may result in the formation of comparatively large aggregates, whereas rapid freezing leads to small ice crystals and small aggregates. As water expands on freezing of wet soils the high pressures that develop can often form very stable aggregates. Freezing of puddled, poorly-aggregated fine-textured soils, is also known to favor aggregation.

If a well-aggregated soil undergoes freezing it is very likely to lead to a breakup of the large aggregates into smaller ones. The small ones may not be affected appreciably. It has also been observed that where freezing does break up aggregates it is likely that many of these will coalesce to form larger aggregates soon after the freezing period is over. This process would probably be favored by the presence of organic matter.

Studies by Bisal and Nielsen (1967) confirm some of the above statements. They state that no general statement of the effect of freezing and thawing on aggregate size can be made that is applicable to the soils that they studied; in fact, these physical changes produced essentially no difference in water-stable aggregates. At low moisture levels there was as much evidence for consolidation as for disintegration. Frost action decreased the percent of erodible particles in a loam soil, and was therefore less erosive in the spring than in the fall. At higher moisture levels freezing and thawing also decreased the percent of erodible particles in both clay and fine sandy loam soils.

When thawing occurs, soils are subjected to the effects of wetting, discussed above, and some of these effects cause aggregate deterioration. It is not always possible to draw a clear line of distinction between the freezing and wetting effects.

Cultivation

The effect of cultivation on aggregation is closely dependent upon the amount of moisture present at the time of cultivation (Russell, 1938; Marshall, 1959, 1962). Other factors involved include kind of soil, amount of organic matter present, intensity of cultivation and the amount of compaction involved. The optimum moisture covers a very narrow range. If moderate cultivation occurs within this moisture range soil aggregation is likely to be improved, especially in soils of medium or heavy texture that were initially poorly aggregated. Cultivation brings the soil particles closer together, thereby increasing the binding forces that favor aggregate formation, but such newly-formed aggregates may show little water-stability. Other factors, including organic matter, are essential for stabilization.

Cultivation of soils, other than those that are very sandy, is usually injurious to aggregation if the soils are too wet. Under such conditions a partial puddling can occur and the result on drying may be a very compact cloddy, poorly-aerated soil. This bad effect increases as compaction, brought about by heavy machinery, increases. The presence of abundant organic matter markedly decreases any harmful effects of cultivation; in practice, its effect is to widen the optimum moisture range at which cultivation can take place without harmful effects.

Cultivation of soils that are somewhat below optimum moisture will produce less damage to aggregates but the production of a good seedbed under such conditions requires more intensive tillage. The cultivation of a very dry soil will result in the shattering of some of the clods and the production of many dust particles. The overall effect on aggregate formation in such a soil, apart from the breakup of clods, is negligible. If the main purpose of the cultivation is to break up clods it is advisable to wait until moisture conditions are more favorable.

Soils that are regularly tilled are likely to show a gradual decline in water-stable aggregates (Neal, 1953) but nevertheless such tillage is usually necessary for the preparation of a suitable seedbed for many crops. The decline in stable aggregates is due in part to the manipulation of the soil when moisture conditions are not optimum, and also in part to the increased oxidation of organic matter. When aggregates are broken down they are not readily or rapidly reformed, resulting in a decrease in ease of water infiltration and poorer aeration. Accompanying these changes is a narrower range of moisture within which tillage is feasible. A well-aggregated soil, having very stable aggregates, can be cultivated satisfactorily over a wider range of water content than can a poorly-aggregated one. Such a soil behaves under tillage as though it contains more sand than is shown by analysis.

The gradual decrease in organic matter and in aggregation that usually occurs in soils that are regularly cultivated over the years is normally attributed to the better aeration produced by cultivation, but this is only a partial explanation. Actually oxygen is seldom very limiting in the average field soil except during periods of high rainfall. Rovira and Greacen (1957), and others, have shown that the increase in organic matter oxidation is largely attributable to the exposure of organic matter that was inside the small pores and aggregates, and inaccessible until these aggregates were disrupted by tillage. Wetting and drying, freezing and thawing, and any other processes or agents that disrupt aggregates would certainly have similar results, perhaps superimposed on other effects that might be involved.

Microorganisms

Soil microorganisms play a role in both aggregate formation and stabilization, and it is frequently impossible to separate sharply the two effects (Martin, 1945a, 1946; McCalla et al., 1957; Jacks, 1963). The amount and kind of organic matter present in the soil and the environmental conditions markedly affect the numbers and kinds of microflora present, which in turn are responsible for the products formed from the organic matter on decomposition.

Microorganisms influence soil aggregation in two ways: (1) by holding the soil particles together by adhesion and by mechanical binding; and (2) by the production of polysaccharides and other organic substances that act as glues or cements. The first of these mechanisms involves aggregate formation chiefly; the second mechanism concerns aggregate stabilization, primarily (Harris et al., 1964), and will be discussed below in the appropriate section.

Aggregate formation by physical entanglement of clay particles is sometimes said to be important where the soil conditions are favorable for the abundant development of filamentous microorganisms, primarily fungi. The chief requirement is for an abundance of available energy materials for their growth. But such energy materials act as precursors of polysaccharides and other glue-like substances. Filamentous fungi (Bernier, 1958), as well as bacteria, can produce such substances and this complicates the determination of the relative importance of physical entanglement vs cementing action. Bacteria appear to play a negligible role in mechanical binding but act primarily through their products of decomposition, and it is probable that this statement also holds for fungi and actinomycetes.

Earthworms

It is now generally recognized that under favorable conditions of moisture, pH, and food supply, earthworms are an important factor in soil aeration and aggregation of loams and fine-textured soils (Guild, 1955; Hoeksema and Jongerius, 1959; also see discussion in Chapter 4). In humid regions soil populations of 500,000 to 1,000,000 per acre are not uncommon and their numbers are sometimes several times this large. Teotia et al. (1950) reported that under some conditions the weight of wormcasts produced per acre per year in Nebraska was as high as 41 tons. Harris et al. (1966) state that during 6 months of the rainy season in the Valley of the Nile in the Sudan a record 107 tons of soil per acre was brought to the surface. Occasionally estimates have been as low as one or two tons of soil per acre but values of 10–20 tons are common. As pointed out in Chapter 4, some species of earthworms do not come to the surface to deposit casts and wherever these species are present the soil turnover is likely to be underestimated.

Most earthworms are voracious feeders on vegetation of various kinds, but especially on the more nutritious and succulent plant materials, such as grass clippings, green leaves and miscellaneous parts of vegetable crops that fall to the soil surface or are incorporated into it. Grass sods are a favorite habitat for the worms. In studies on old pastures Evans (1948) estimated that 4–36 tons of soil per acre per annum pass through the alimentary tracts of earthworms. He also observed that the percentage of pore space in a soil containing a high population of wormcasting species was much greater than that of a field with a high population of worms that did not produce casts. In these old pasture soils the amount of coarse sand relative to silt and clay was found to increase with depth, suggesting that the long-continuing activity of earthworms had moved the finer particles to the surface. These results strikingly demonstrate the importance of earthworms in soil aggregation when conditions are especially favorable for them.

Earthworms are also fairly common in cultivated soils but constant cultivation is likely to reduce their numbers both by mechanical disturbance and by elimination of the surface layer of decaying plant material on which they feed (Barley, 1959a). Where the worm population is high, and a thin layer of suitable vegetable matter is placed on the soil surface, it is not unusual to note that most of it will disappear within a few days. It is dragged into their burrows or tunnels and consumed at their leisure.

Claims have been made that chemical fertilizers are harmful to the worm population. The writer has personally observed that this is not the case. If such fertilizers are placed in contact with the animals they may be killed but, given a chance, they will avoid the fertilizer until the concentration is no longer harmful. If such fertilizers are added to unproductive soils, and suitable crops planted, the worm population is likely to increase severalfold within a year or two if moisture is adequate. This is the normal response to the increased food supply that is made available as a result of added fertilizers.

Increased soil aggregation is produced by earthworms as a result of a number of mechanisms, all combined, that involve both formation and stabilization. The process of burrowing through the soil has some direct mechanical effect on aggregate formation and even more of an effect on aeration and water movement. The main effect, however, is brought about by the swallowing of large quantities of soil and organic matter from which they digest much of the organic matter and discard the organic and inorganic residues as casts. As this soil passes through the gut of the animal it usually increases in pH and lime and is thoroughly mixed with organic matter, largely from outside sources. The mineral particles undergo some comminution and the organic matter is disintegrated and digested both by the digestive juices in the alimentary tract and by the mass of microorganisms that quickly develops in this ideal habitat for their multiplication. The voided casts then consist of well-kneaded soil, millions of bacteria, undigested organic matter, and microbial synthetic products, all in intimate mixture and discarded on the surface to dry into aggregates that are fairly stable, at least for a time.

It is not possible to evaluate quantitatively the importance of the various factors involved in the process of earthworm formation of aggregates. Although the earthworms are definitely responsible for the molding of the organic–inorganic aggregates it is likely that their stabilization is largely the result of the cementing materials formed synthetically by bacteria in the intestinal tract, and therefore may be of short duration. Nevertheless the earthworms, by initiating the process, may contribute materially to aggregate formation and improved tilth. Drying helps to stabilize the aggregates in casts deposited on the surface.

Claims have been made from time to time that the construction of worm tunnels in fine-textured soils increases the ease of water movement. This is true if pore space is increased appreciably by worm activity but, as Barley (1959b) points out, freshly constructed tunnels are too wide to conduct water at the tensions encountered during infiltration. He considers that plant roots are probably more important than worms in modifying pore space distribution.

Other soil fauna (see Chapter 4) should also be given some credit for improvement in soil aggregation and pore space, but present evidence indicates that earthworms are usually of more value in these processes than are all of the other fauna combined (Edwards and Heath, 1963).

Plant growth

The best aggregated soils that exist anywhere are those that have been continually in grass for many years (Martin, 1944; Mazurak and Ramig, 1963). Even a poorly-aggregated soil of medium or fine texture will show a marked improvement in aggregation after three to five years or less in grass (Emerson, 1954), but a much longer period is required for the soil tilth to approach that of a virgin chernozem soil (Low, 1955). When a sod is broken and the soil is planted to tilled crops a rapid deterioration in aggregation occurs. The new equilibrium that is eventually established will depend upon the numerous physical, chemical and biological factors that are active. These are almost too numerous to mention and the relative influence of each varies with time. Briefly they include type of soil, crops grown, climatic factors, type and degree of cultivation, organic matter additions and numerous other less important factors that may be grouped under the heading of farm management practices.

Improvement in soil aggregation is not a benefit that is realized from sod crops exclusively, but aggregation reaches its maximum with such a crop. All crops that grow on a reasonably normal soil tend to improve aggregation, but other factors, such as cultivation, may be working in the opposite direction, thereby masking the effect of the plant (Barber, 1959; Harris et al., 1966).

Plants exert their beneficial effects on aggregation chiefly in the following ways: (1) they protect the soil surface from raindrop splash and other weathering effects; (2) they have a mass of fine roots that ramify throughout the topsoil, exerting pressures that may help to form aggregates; (3) they continually remove water wherever the root hairs are in contact with the soil grains, and the local drying produces stresses and strains; (4) they furnish food to the rhizosphere microorganisms that may directly or indirectly play a role in aggregation; and (5) they are a continuous source of soil organic matter.

Exposed fine-textured soils without mulch or growing vegetation commonly form a hard surface crust on drying after a heavy rain. This is due chiefly to the forces exerted by falling raindrops that tend to break up any aggregates that they hit. A good cover of crop residues or growing vegetation absorbs the force of the falling rain and thus protects any aggregates present. The cover also often serves to keep the aggregates moist and thus minimizes the destruction caused by the escape of air as rainwater wets the soil mass.

The root systems of plants, especially of grasses, are very extensive (see pp. 335–341). As these roots push through the soil they exert considerable pressure which forces clay particles together and thus favors aggregate formation. The roots may possibly occasionally penetrate aggregates and break up some of them but this does not seem to be a major effect; their growth is chiefly between aggregates. The pressures exerted by the growing roots continue so long as the plants grow, and there is considerable local variation in pressure as older roots and root hairs die and newer ones are formed. It is a common observation that the beneficial effects of plants on soil aggregation vary directly with the total mass and fineness of division of the root system. Plants with large taproots and limited root hairs, such as cotton and soybeans, are less effective in aggregate formation than are grasses.

Pressure alone, it should be emphasized, is not adequate for producing satisfactory water-stability (Rogowski and Kirkham, 1962), but it is certainly one of the important contributing factors in aggregation.

More important than the direct pressure effects of the growing root system are the never-ending effects of moisture changes in the soil brought about by plants. Uncropped soils also undergo moisture changes, but in this case the tendency is for the changes to be mass ones. In contrast, in cropped soils each little rootlet is taking water from a very limited local micropore or from a microportion of soil. On a microscale these rootlets may seem far apart; one bit of soil may be undergoing rather rapid drying whereas other soil that is actually not far away may be showing no appreciable moisture changes. These stresses and strains produce particle movements and orientation that favor aggregate formation when moisture conditions are favorable. The drying effects also tend to make more resistant any colloidal films that may surround aggregates already present or being formed.

Plants are constantly sloughing off root cells or entire root hairs. They are also releasing organic and inorganic compounds to the soil solution. The result is a medium that is favorable to the growth of a diverse flora of fungi, bacteria and actinomycetes. As already stated, some of these may aid aggregate formation by mechanical means. They also favor aggregate stabilization by secretion of polysaccharides and other substances that help bind particles.

Plants are of course the ultimate source of all organic matter in the soil and this is one of the main reasons why heavy continuous cropping favors aggregation. The crop roots and any portions of the tops that reach the soil by whatever method serve as the precursors of humus. In humid regions certain forms of organic matter are the important ingredients that make the difference between good and very poor aggregation. Plant roots are especially valuable for this purpose, because they are naturally present where they will do the most good. On the growing plant they are the continuous source of food for a mass of microorganisms. After the plant dies the roots still furnish an energy supply for many months but necessarily at an ever-diminishing rate.

Aggregate stabilization

Many factors are involved in aggregate stabilization and many theories have been advanced to explain what takes place. There is obviously no simple explanation that applies to all situations, but there is general agreement that both organic and inorganic compounds play key roles, although in different degrees and ways in different soils. Greenland (1965a,b) and Harris et al. (1966) have presented fairly complete reviews of the subject that emphasize the complexities involved.

Proposed mechanisms

The suggested mechanisms for the formation of water-stable aggregates, according to Harris et al., include: "(a) linkage of clay particles by water dipoles; (b) cross-bridging and sharing of intercrystalline forces and interaction of exchangeable cations between oriented clay plates; (c) envelopment of soil particles by precipitated and irreversibly dehydrated colloids, e.g., silicates, sesquioxides, and humates; (d) aggregate stabilization against water entry by the presence of hydrophobic organic materials, such as fats and waxes; and (e) interparticle linking by organic polymers that form bonds through their functional groups with the surface of 2 or more clay particles." They point out that hydrophilic or hydrophobic organo-clay complexes may play a role in the interlinkage of clay particles, followed by dehydration or precipitation.

Harris et al. also point out that "the aggregating effectiveness of organic polymers is a function of molecular weight, configuration, and the number of amino, hydroxyl, or carboxyl functional groups present on the polymer molecule. Uncharged organic polymers probably link clay particles together by hydrogen bonds between the polymer hydroxyl groups and the surface oxygens of the basal sheets of the clay crystals, or by the establishment of nonspecific Van der Waals forces with the clay surfaces. Polyanions link clay particles together by chemical bonds formed between the polymer functional groups and the outside edges of the clay crystals. Anion exchange, hydrogen bonding, and cationic bridge formation are possible mechanisms for clay-polyanion linkage."

Greenland states that on the basis of present knowledge "it seems probable that adsorption of humic materials takes place predominantly through ionic linkages involving polyvalent cations or oxides as intermediates between the humic material and clay particle, whereas adsorption of polysaccharides is primarily due to physical adsorption forces." He stresses the importance of polymer size, shape and charge characteristics.

Effectiveness of various kinds of organic matter

The statement is often made that there is a close correlation between the amount of organic matter in soils and the degree of aggregation and tilth. This is generally true but it is well to bear in mind that not all kinds of organic matter act as effective stabilizing agents. Materials such as peat, sawdust, and essentially all kinds of undecomposed crop residues have little effect in the stabilizing of aggregates, although they do help to keep aggregates small. As organic matter sources undergo decomposition, microbial slimes are produced that do have marked stabilizing properties (Quastel, 1952; Chesters et al., 1957). The quantity produced per unit time is usually directly related to the amount of crop residues present and their rate of decomposition. These microbial gums consist largely of polysaccharides, polyuronides, cellulose and humus breakdown products, and other linear organic polymers.

Since it is primarily the products of microorganisms that are the stabilizers, it is obvious that even well-rotted manures and composts are not especially active as stabilizing agents. The immediate effects that they produce are largely dependent upon their content of microbial slimes and related materials at the time that they are used. If they contain considerable available energy sources then, as they undergo further decomposition, microbial gums will be synthesized which will have the usual favorable effect on aggregation if they contact the aggregates and act as cements before they themselves undergo decomposition. Manure that has been stored under anaerobic conditions, for example, is obviously not thoroughly decomposed and when exposed to the air the aerobic flora can synthesize abundant supplies of polysaccharides. Peat and other comparatively inert materials may act to improve heavy soils both by dilution and increased water absorption.

Humic acid or humates of high molecular weight also usually have a limited effect on aggregate stabilization. These molecules are too large, are spherical instead of linear, have an undesirable configuration, and only a limited number of functional groups that are free to attach themselves to clay particles. They are essentially inert. According to Emerson (1960), humic acid is too easily removed to be the important polymer in soil organic matter for stabilizing soil crumbs. When added as soluble sodium humate the effectiveness is much greater than that of the insoluble humic acids and humates. This is in line with the established fact that water solubility is an essential, or at least a very important, property of effective aggregate stabilizers.

The above statements regarding the effectiveness of different kinds of organic matter in aggregation apply to organic matter that is incorporated with the soil. Actually most any kind of organic matter that is used as a long-time mulch will improve aggregation and structure, but this may be largely through prevention of raindrop splash, improved moisture conditions, higher earthworm populations and lack of mechanical disturbance.

Microbial gums, as pointed out below, may also be an important factor if the mulch materials serve as food for microorganisms.

Polysaccharides and related natural substances

Microorganisms are the agents that are responsible for the production of a variety of linear organic polymers that are important in aggregate stabilization (Martin, 1945a,b, 1946: Keefer and Mortensen, 1963). These substances include low molecular weight humic substances and various polysaccharides, or polyuronides, that are produced by many species of bacteria, fungi, actinomycetes and yeasts (Forsyth and Webley, 1949). Microbial species vary widely in their ability to produce such substances. Green plants also produce plant polysaccharides and other closely related compounds that are able to increase the stability of soil aggregates (Quastel, 1954; Martin et al., 1955) but present evidence indicates that these plant substances play a minor role in soils. This is because they are rapidly decomposed by microorganisms and there is little opportunity for them to act as stabilizers. The products formed by the soil organisms from these substances and from other energy sources are likely to be more widely distributed in the soil mass and are more resistant to decomposition, especially when in intimate contact with the soil particles.

Early studies by Kroth and Page (1947) showed, in fact, that the natural polar aggregating agents formed from decomposing organic matter were uniformly distributed throughout aggregates, and in contact with each particle. They observed no sign of coatings on these aggregates which could act in a protective capacity.

Numerous studies, such as those of Martin et al. (1965), have shown that microbial polysaccharides show widely different degrees of stability against decomposition in soils. A few species, mostly fungi and actinomycetes, are able to decompose at least some bacterial polysaccharides readily whereas the growth of other organisms, mostly bacteria, is actually inhibited by some of these bacterial gums. In other studies the same workers (Martin et al., 1966) have shown that the salts or complexes of iron, aluminum, zinc and copper with some microbial polysaccharides are much less susceptible to decomposition than are the untreated bacterial gums. The effects of the metals on ease of decomposition of the polysaccharides did not follow a set pattern but exhibited marked specificity. Since these determinations of resistance to decomposition (Martin et al., 1965, 1966) were made in soils it is not possible to know how much of the resistance of a given polysaccharide or complex should be attributed to the substance itself, and how much to the protective action of the soil.

Under most soil conditions it is the aerobic microflora that is responsible for the formation of aggregating substances, but Harris et al. (1963) showed that the anaerobic microorganisms also possess this ability. This is shown in Fig.16.1, taken from their publication. In this experiment the stability of artificial sucrose-amended soil aggregates was determined under both aerobic and anaerobic conditions. Under aerobic conditions aggregate stability increased rapidly for 4 days to 80% and then fell nearly as rapidly to zero stability after 12 days. Under anaerobic conditions aggregate stability increased slightly more rapidly during the first 4 days and reached a value of 100% after 15 days. This value was maintained until the end of the 4-week experiment. Later experiments showed complete stability of these sucrose-amended aggregates after 8 weeks of anaerobic incubation. In contrast, similar aggregates that had been maintained under anaerobic conditions for 15 days were completely unstable after aerobic incubation for 9 days. Obviously the anaerobes were able to form organic aggregating agents from sucrose but could not utilize these products as energy sources, whereas the aerobes could utilize the aggregating substances produced by either group of organisms.

The ability of anaerobes to form gums that they cannot decompose can under some conditions act to seal soils so that they are largely impermeable to water. Allison (1947) and McCalla (1951) observed that when soils were submerged for long periods of time, the soil pores became clogged with microbial cells and slimes (polysaccharides). This presents a problem in irrigation but in reservoirs or ponds such a sealing would be desirable.

A hypothetical model of how clay and organic matter may be arranged within an aggregate is shown in Fig.16.2, which was drawn by Emerson (1959). Clay crystals are known to be grouped together in packs, or domains of oriented platelets that behave as units in the presence of moisture. These unit packs may occur in various juxtapositions with relation to each other and to particles other than clay (Gieseking, 1949). Suitable types of organic matter, perhaps of molecular thickness, may assist in binding the inorganic constituents, as shown in the figure. Emerson points out that the figure is oversimplified, and that many possible arrangements in a soil crumb are possible. In Fig.16.2 at *A* the quartz particles are shown linked directly by organic matter; at *B* the organic matter is shown acting as a cement between quartz and clay packs; at C_1, C_2 and C_3 the clay packs in different positions are linked by organic matter to each other; and at *D* some clay domains are shown held together by electrostatic attraction between positive edges and negative faces, with no organic matter involved. When quartz is coated with sesquioxides the strength of the quartz-clay bonds may be greater than in the absence of these oxides. Emerson also points out that in normal agricultural soils, where calcium is

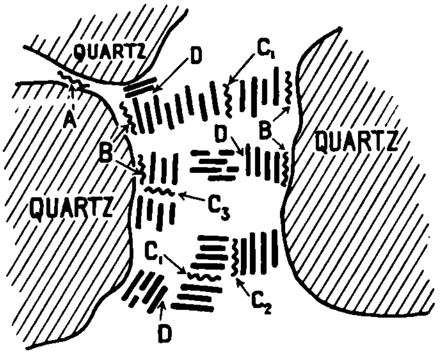

Fig.16.2. Possible arrangements of domains (packs), organic matter, and quartz in a soil crumb. (Redrawn from Emerson, 1959.)

the main exchangeable cation, the clay crystals in the crumbs are aggregated into domains or packs by drying to the wilting point. Lime may also act as a substitute for organic matter as a stabilizing agent; other substances, such as artificial soil conditioners, can perform the same function. Emerson emphasizes that Fig.16.2 does not hold for all soils and conditions, but it does illustrate types of mechanisms encountered in soil stabilization. The review by Harris et al. (1966) mentions other possibilities.

There have been many experiments, conducted in the laboratory, greenhouse and field, showing that the addition of available energy sources to soils will bring about increased soil aggregation but such aggregates are usually water-stable for only a comparatively short period of time. Usually the more available the energy source the more rapid the increase in aggregation and the sooner the aggregates break down. The effect of sucrose, as shown in Fig.16.1, is realized very quickly but may disappear after two weeks under conditions suitable for the growth of aerobic organisms. The addition of crop residues usually produces a more moderate effect on aggregation but the effect is a little more lasting (Browning and Milam, 1944).

Even though most microbial polysaccharides are not very resistant to biological attack, chemical studies (Mehta et al., 1961) have shown that soil organic matter commonly contains 5–20% of polysaccharides composed of many sugars. Their extreme heterogeneity confirms that they are predominantly of microbial origin. This poses the question: why do these carbohydrates tend to persist in soil? There are several possible explanations: (1) some polysaccharides may be naturally resistant to decomposition; (2) complexing with metals increases resistance; (3) enzymatic repolymerization in the soil of polysaccharide structural units including whole or parts of molecules, may occur, as suggested by Martin et al. (1966); (4) bonding between active groups of organic compounds and clay minerals (Greenland, 1965a,b), especially inside the lattices of 3-layer minerals (Pinck et al., 1954), protects them; and (5) organic substances may be held inside of aggregates where they are largely shielded against biological attack (Emerson, 1959). Further research is needed to assess the value of these possibilities, but in the opinion of the writer, the fourth and fifth possibilities mentioned above are the ones that deserve emphasis. There is some inadequate evidence, mentioned above, in support of the first two explanations, but the third suggestion scarcely deserves serious consideration, since there is always an abundant mixed hungry microflora present to consume any polysaccharide structural units that might be formed or set free.

In Fig.16.2 organic matter (polysaccharides) is shown as an active binding material between soil particles. This is probably present as a monomolecular film. If so, this helps substantially in explaining its resistance to decomposition. Emerson states that on the basis of the model, the amount of organic matter that is resistant to microbial attack would be proportional to the surface areas of the clay packs. If the aggregates are broken down mechanically, as by tillage, some of the organic matter in the bonds is set free for microbial attack. This is in agreement with the results of Rovira and Greacen (1957), already mentioned. Microorganisms are much too large to attack a film of organic matter of molecular thickness, bound between soil particles, until it is set free.

Present evidence, presented in part above, indicates that polysaccharides are well protected against decomposition when, and usually only when, bound within an aggregate or in a clay lattice. If so, it follows that in a well-aggregated and undisturbed soil where stabilization is dependent on polysaccharides or other readily decomposed substances, a steady state condition should exist. This means that if the soil aggregates have an abundant supply of polysaccharides, and more are being produced, these newly-formed materials should be decomposed readily because they are unprotected. No one knows whether protected polysaccharides remain protected for only a short time or for months or years. Many factors would determine this but any disturbance of the steady state condition that resulted in their release might allow some newly-formed polysaccharides to enter aggregates, and in turn become protected. If the organic materials that act as cements are securely protected, the ratio of the quantity being produced to the amount needed for binding at any one time might often be large. This would lead to a rapid decomposition of most of the polysaccharides as they are being produced, and this is what we know actually happens. Since polysaccharides act as aggregate-stabilizing substances in highly stable aggregates, and not as aggregate-forming agents, a steady state condition could exist in an undisturbed soil at any level of aggregation.

These facts have important practical applications. The frequent turning under of masses of crop residues or green manures (Martin, 1944; Benoit et al., 1962) is not likely to do much to improve aggregation (a fact now well known) unless polysaccharides and other organic binding materials are inadequate (unlikely under steady state conditions), or unless new aggregates are being formed that are capable of being made highly stable. The microbial gums may help to form temporary unstable aggregates, as discussed above, but these are of negligible value, and their importance has been greatly over-emphasized for many years.

Microbial penetration into stable aggregates

Most soil scientists who are active in soil aggregation studies, such as Emerson (1959), Marshall (1962), and Edwards and Bremner (1967a,b), seem to hold the opinion that microorganisms are too large to penetrate into *stable* aggregates but remain outside where the roots are found. Acceptance of this idea is fundamental to our understanding of aggregate stability. No one, so far as I know, has attempted to isolate a bacterium from inside an aggregate, and hence all evidence for or against their presence there is indirect. This evidence is of three types: (1) the persistence of proteins and other organic substances in clay lattices and aggregates; (2) their rapid decomposition when released; and (3) the relative sizes of microorganisms and spaces between particles within an aggregate.

First, many workers (Pinck et al., 1954) have shown that a monolayer of protein inside of clay lattices is not decomposed readily. Others (Rovira and Greacen, 1957; Emerson, 1959; Marshall, 1962; and Edwards and Bremner, 1967a,b) have indicated that the same is true of organic matter that is bound inside of soil aggregates. For example, Edwards and Bremner concluded that their studies were "consistent with the theory that the process of microaggregate formation stabilizes some of the organic matter in soils by rendering it physically inaccessible to microorganisms."

Second, many workers have observed that disruption of aggregates by most any method allows microorganisms to decompose rapidly some of the organic matter not previously available to them.

Third, a layer of protein inside the lattice of montmorillonite has a thickness of about 4.8 Å (Pinck et al., 1954). A layer of polysaccharide should be slightly thinner. Soil bacteria are usually 0.5–1.0 μ (5,000–10,000 Å) and fungal filaments 2–10 μ (20,000–100,000 Å) in diameter. Hence, the smallest bacteria are about 1000 times thicker than the polysaccharide layer in stable aggregates. As Emerson's model (Fig.16.2) shows, there are air spaces inside of aggregates and this may mean distances considerably greater than 5 Å, especially if particles larger than clay are present. Very likely in such less-stable aggregates, a few organisms might be able to gain entrance, and some might be trapped inside when the aggregate is formed. Such organisms would probably find conditions for growth unsatisfactory, and if they did grow, cell multiplication would soon split the aggregate. Stable aggregates (250 μ diameter) as described by Edwards and Bremner seem to remain intact. In contrast, aggregates such as those of Harris et al., held together loosely by bacterial gums, are rapidly disintegrated by microorganisms or their enzymes. The wet-sieve method, as ordinarily used, does not differentiate between such non-stable aggregates and the bacterial-free stable ones as described by Edwards and Bremner. This is why results obtained by this method often have little practical meaning.

Synthetic soil conditioners

The bringing about of a satisfactory state of aggregation in many soils, and the maintenance of this state, present many problems. Often almost the only practical method for doing this is to use a rotation that provides for the periodic use of sod crops. On high-priced land, and where the area available is limited, this is often an expensive practice. It is these facts that lead to the development of synthetic soil conditioners that can act as aggregate stabilizers but are not decomposed rapidly, if at all, by microorganisms (Quastel, 1954; Harris et al., 1966).

Four Krillium-type conditioners that have been prepared are polyacrylic acid (PAA), polyacrylonitrile (PAN), hydrolyzed polyacrylonitrile (HPAN), and vinyl acetate–maleic acid copolymer (VAMA). Other possible conditioners include carboxymethylcellulose (CMC) and polyvinyl alcohol (PVA). These compounds have many properties that are similar to microbial polysaccharides, and they may act by like mechanisms in binding soil aggregates. The polymer molecules bridge the gap between two or more clay particles. They are also capable of being strongly adsorbed on clay and thus may form anchor points for bridging. If the linear polymers are sufficiently large and flexible to make contact at several points the binding power is unusually strong. The synthetic compounds are effective in concentrations of about 0.1–0.2% (per unit dry weight of soil).

Synthetic soil conditioners do not form aggregates but they are strong stabilizers of those that are already naturally present in the soil, or formed mechanically. This is one outstanding case where there is a sharp line of distinction between formation and stabilization of aggregates. The synthetic polymers combine with soil particles very quickly in the presence of adequate moisture and they do not move appreciably afterwards. Cultivation tends to cause crumb breakdown and these conditioners do not act a second time as stabilizers, since they are no longer water soluble.

The sponsors of synthetic soil conditioners initially had high hopes that they would be of great value in agriculture. This did not prove to be the case for various reasons, chiefly cost of materials, lack of aggregate forming ability, difficulty of application, and disappearance of most of the benefits after one season.

Inorganic binding and clay skins

Many red and yellow tropical soils (latosols) that do not harden into laterites contain little clay of the montmorillonite and illite types, and have a low organic matter content. Nevertheless, these soils have a fairly good structure and can be cultivated satisfactorily (Nye and Greenland, 1960; Sivarajasingham et al., 1962). The existence of such soils shows clearly that no one mechanism can account for the development of suitable structure and tilth. In latosols it is largely the process of mobilization and deposition of iron and aluminum oxides, amorphous silica and carbonates that accounts for aggregate stabilization. It is of interest that Lutz (1936) was a pioneer in stressing the importance of iron as a cementing agent in soil aggregation but comparatively little research was done on this for several years.

Uehara et al. (1962) call attention to the excellent physical properties of latosols found in Hawaii. These soils that consist almost wholly of kaolin and free iron oxide are well aggregated and have withstood the use of heavy agricultural equipment. They stress the importance in stable aggregate formation of: (1) nature of the soil minerals; and (2) the arrangement of these minerals within the soil pedological units and the process by which these arrangements come about. The oxide system in these soils may be either the hydrated or non-hydrated forms of iron and aluminum but the iron system is usually predominant. It is the hydrated iron oxide coatings that serve as a cement on the finer kaolinite particles that have been oriented, either by clay movement from overlying horizons or by external pressures that are caused by wetting and drying, soil creep, etc. The authors suggest that the probable mechanism of cementation may be through hydrogen bonding between kaolinite and free oxide.

The subsoils of yellow-brown earths (rainfall above 35 inches), according to Fieldes (1962), are made up of nutty aggregates and contain considerable amounts of hydrous oxides of iron, aluminum, and silica. He states that it is probable that the good structure of these soils is promoted by cementing both of free iron oxides, and by allophane-like materials (aluminosilicates). In electron micrographs of untreated clays he observed iron oxides adhering to platy clay particles.

Marshall (1962) points out that many soils with small amounts of oxides of iron and aluminum are also affected. But the mere presence of free oxide and kaolin does not necessarily result in good structure; the degree of particle orientation is also very important (Uehara et al., 1962; Cagauan and Uehara, 1965).

Certain acid soils, rich in hydrated iron oxide and containing considerable humus, were found by Filippovich (1956) to have a very stable structure. Accumulation of humus in these soils did not improve the structure unless accompanied by much colloidal hydrated iron oxide. Adsorption of the mixed colloid on large soil particles resulted in a stable structure. He also points out that where soils are high in both calcium carbonate and iron, a good soil structure may result from the conversion of soluble iron salts into colloidal insoluble hydrated iron oxide.

Iron oxide may also increase the beneficial effects of organic matter (Chesters et al., 1957). McIntyre (1956) concluded from studies of soils in South Australia that the chief influence on the structure of these soils is iron acting through the medium of an iron–organic matter complex. In semi-arid soils calcium and magnesium carbonates may also act as cements. These materials are carried in the soil percolate and a portion is deposited on aggregates, or may form hardpans at lower levels.

Under ideal conditions of aggregation nearly all of the aggregates in soils of mild climates are in the range of 0.25–5.0 mm in diameter. This is the condition that commonly exists in permanent grasslands. If many of the peds (aggregates) attain sizes much larger than this the soil approaches the cloddy condition and is no longer considered to have good aggregation and tilth. There has been considerable interest in the reasons for this size limitation. Soils containing much clay are not static but in the presence of moisture the particles are subject to movement in all directions as moisture and temperature change. In fact, essentially all of the factors discussed above that are active in aggregate formation also play a role in aggregate size limitation.

Clay skin or cutan (see Brewer, 1960) formation on aggregates is a subject that has been given considerable attention by soil geneticists (Hendricks et al., 1962) but too little by those interested in aggregation and stabilization. Buol and Hole (1961) define a clay skin, or coating, as "the assemblage of optically oriented clay (0.002 mm), with included coarser particles, formed on the walls of interstices in the soil and exhibiting abrupt internal and external boundaries." They state that in well-drained soils clay skins contain larger proportions of iron or organic matter, or both, than the surrounding matrix. They are apparently formed from clay carried down by water from the upper layers of soil and deposited at lower levels in an oriented manner. Clay coatings have been observed in soil profiles of many great soil groups.

Analyses of clay skins removed from peds in the B_3-horizon of a gray-brown podzolic soil from Wisconsin were made by Buol and Hole (1959, 1961). A portion of these data, as well as a similar analysis of the entire B_3-horizon, are shown in Table 16.I. These analyses show that the clay skins were much higher in N, C, free Fe, P and Mn than was the bulk sample. Microscopic thin-sections of the clay skins showed a range of thickness from 0.016 to 1 mm. A mean cross section with five distinct layers was 0.079 mm thick. In some cases clay skins were embedded in aggregates and lined both the root channels and the roots. In the upper part of the B-horizon the clay skins were thicker and more numerous than in the lower B-horizon. Apparently organic matter plays an important role in their synthesis.

According to Buol and Hole (1961) clay skins form chiefly in soils with relatively

TABLE 16.I

SOME PROPERTIES OF THE B_3 HORIZON AND ITS CLAY SKINS IN A GRAY-BROWN PODZOLIC SOIL, OCKLEY SILT LOAM (from BUOL and HOLE, 1959)

Element, compound or ratio	*Data for clay skin from the B_3-horizon**[1] (%)*	*Data for total B_3-horizon**[1] (%)*
N	0.11	0.029
C	1.836	0.417
Organic matter*[2]	3.094	0.714
C/N ratio	16.7	14.4
Clay	87.4	24.3
Free iron (Fe_2O_3)	3.95	1.90
Na	0.39	0.79
K	1.38	1.55
Ca	0.1	0.1
Mg	0.72	0.48
Fe_2O_3	8.1	4.5
TiO_2	0.66	0.75
SiO_2	49.8	70.7
Al_2O_3	18.8	13.1
$SiO_2/Al_2O_3 + Fe_2O_3$	3.5	7.5

*[1] Percentages based on 105°C weights.

*[2] Carbon content × 1.72.

stable aggregates and root channels. They also form in very small increments of minute lamellae (plates). Considerable clay is essential for skin formation, and time is a factor. Any disturbance of the soil as by wetting and drying, freezing and thawing, and even microbial action causes the fragmentation of clay skins in the surface soil and the incorporation of the fragments into the interior of aggregates. Less disturbance at lower soil depths permits more stability of the clay skins in that region. They probably serve as a colloidal membrane that protects the bulk of the soil from leaching.

In studies by Khalifa and Buol (1968, 1969) continuous clay skins were found on ped faces, in pores and around root channels in the B-horizon of Cecil soils from North Carolina; discontinuous clay skins were observed along vertical pores in the C-horizon. They state that "compared to the whole peds from the B_{22t}-horizon the clay skins contained more clay, fine clay ($< 0.2\ \mu$), total iron, free iron, Al_2O_3, K_2O, P_2O_5, and total N; less silica and gibbsite than the whole soil peds." Wheat plants grown in the uncoated aggregates had higher dry weights and more total N, P and K than those grown in either the large or small coated peds. Fine roots were concentrated on the surface of the clay skin. It was hypothesized that the clay skins reduced plant growth and nutrient uptake, either by acting as a barrier or by retarding ion diffusion from the peds into the soil solution, or both.

In greenhouse studies Barrows et al. (1966) observed that 12- to 14-mesh calcite limestone particles, placed in acid soils containing large amounts of phosphorus, developed coatings 0.03–0.1 mm in thickness after 7 months. This development of a phosphate coating differs considerably from the formation of a clay skin but it does show that coatings can form comparatively rapidly when the conditions are favorable. Under field conditions the coating, as already stated, can be high in Fe, Al, Mn, and Si, usually with accompanying clay and organic matter.

These various observations would seem to leave little doubt that clay skins play a considerable role in aggregate stabilization, but probably only a minor part in aggregate formation. It would also appear that they are an important factor in limiting the size of aggregates since the coatings tend to form chiefly on the outside of aggregates, in root channels, and wherever water carrying clay, iron and organic matter is free to move. A critical evaluation of their role in aggregation must await further research, but it seems to the writer that under many conditions clay skins can be an important factor in aggregate stabilization. Their effect would be in addition to those brought about by the other factors, discussed above, that are involved in aggregate stabilization.

ROOT DEVELOPMENT

The root systems of various cultivated crops vary widely in size, depth to which they penetrate, area from which they draw water and nutrients, and the fineness of division of the rootlets (Ten Eyck, 1899, 1900, 1905; Weaver, 1926; Laird, 1930; and Pavlychenko, 1942). In general, the plants of the grass family show the most extensive development in the surface soil, and exert the greatest effect in the development of good aggregation. As already stated, all root growth contributes to better tilth, but in soil studies most attention has been given to plants of the grass family because they are so effective, and are used universally in crop rotations for improvement of physical conditions.

Goedewaagen and Schuurman (1950) assembled data on root production by various agricultural crops and found that winter cereals produce a higher amount of roots and stubble in the topsoil than do spring cereals. Among the winter cereals the average amount of roots and stubble in the surface soil was about 2,200 lb. per acre. The minimum was 1,400 lb. for spring barley and the maximum 3,100 lb. per acre for rye. The corresponding value for alfalfa, which increases with age, was nearly 5,500 lb., and for annual leguminous and non-leguminous crops about 800 lb. Nearly 75% of the root system of arable crops is in the surface 0–8 inches. Data for eleven crops gave a value of nearly 400 lb. per acre of roots in the subsoil at a depth between 1 and 4 ft. On several fields of old grassland the average root weight was about 6,500 lb. per acre to a depth of 8 inches, which was 87% of the total root mass. The amount of roots on young grassland was generally lower than on older land, and the roots were less concentrated in the topsoil. The root mass on grassland increases during the spring growth period and decreases during the fall and winter as many roots decay. The average amount of roots produced by grass crops on mineral soils every year was estimated to be approximately 5000 lb. per acre, but this value may be increased to a certain extent by applications of artificial fertilizers.

The type of root system developed by a plant depends not only on soil tilth but also on the level of nutrients present. The root system tends to be more branched and more concentrated in a fertile soil than in a poor one. If a poor soil is fertilized with well-rotted manure, for example, each pocket of manure will be filled with a mass of much-branched roots, whereas the remainder of the soil will have few roots other than the larger primary and secondary ones. Undoubtedly this extreme development of fine roots in manure is a response to chelated minor elements as well as to the major nutrients. If a poor soil is not fertilized with either chemical fertilizers or manure the top–root ratio is likely to be unusually narrow, and the roots may extend to deeper depths (Oswalt et al., 1959). We sometimes say that such roots are long because they are searching for nutrients, but the real explanation is that the carbohydrate level in the root increases as the available nutrient supply decreases. When the nutrients are inadequate for a luxuriant top growth there is a bigger excess of carbohydrates that are transported downward and used for root growth. Inadequate soil moisture in the upper part of the soil profile may also result in a deeper root system.

Many factors affect the development of roots in soils but these need not be discussed here (see Brouwer, 1965; and Barley and Greacen, 1967). Pearson (1966) has given an excellent discussion of the conditions in the subsoil that tend to inhibit growth and which often cannot be improved readily or quickly. These include soil acidity, deficient available nutrients, mechanical impedance, unfavorable moisture, and poor aeration. As he points out, the properties of surface soils can usually be modified readily but after this is done the root systems frequently have to contend with a subsoil environment that severely limits their development.

Number, length and surface area of roots

Detailed quantitative measurements of the number, size and length of entire root systems of plants have been made only infrequently because of the size of the task. Pavlychenko (1942), for example, stated that it required 216 hours for him to measure and describe just one of many nodal roots that developed from the underground stem of a two-year old grass plant.

Dittmer (1937) grew single rye plants for four months in the greenhouse in boxes containing 1.9 cu. ft. of soil. While the plants were still growing vigorously but had not yet flowered, the soil was washed from the roots and counts and measurements made. The data for the roots of a single rye plant are given in Table 16.II and for the root hairs in Table 16.III. The root hair counts and measurements are only for those living at the end of the four-month growth period.

The entire root system of a single plant, exclusive of root hairs, totalled 13,815,672 members with a surface area of approximately 2,554 sq. ft. The combined length of all roots was 387 miles, distributed as follows: main roots, 0.04 miles; secondary roots, 3.37 miles; tertiary roots, 108.74 miles; and very fine quaternary roots, 275 miles.

Root hairs were scattered over the entire surface of all roots of this rye plant, the

TABLE 16.II

THE NUMBER, LENGTH AND SURFACE OF THE ROOTS, OTHER THAN ROOT HAIRS, ON A SINGLE RYE PLANT (from DITTMER, 1937)

Root categories	*Number of roots per unit**[1]	*Total number of roots by categories*	*Average length (inches)*	*Total root length, by categories (ft.)*	*Average diameters (microns)*	*Total root surface, by categories (sq. ft.)*
Main	1.0	143	18.0	214.50	700	1.53
Secondary	249.0	35,607	6.0	17,803.50	250	45.06
Tertiary	16,060.5	2,296,651	3.0	574,162.75	130	758.60
Quaternary	80,302.6	11,483,271	1.5	1,452,075.60	120	1,748.90
Totals	96,613.1	13,815,672		2,044,256.35		2,554.09

*[1] A unit includes one main root with all its secondary, tertiary, and quaternary roots. There were 143 such units on this plant.

TABLE 16.III

THE NUMBER, LENGTH AND SURFACE OF THE ROOT HAIRS OF A SINGLE RYE PLANT (from DITTMER, 1937)

Root categories	*Number of hairs per sample**[1]	*Total number of root hairs by categories*	*Average length of root hairs (microns)*	*Total root hair length, by categories (miles)*	*Average diameters (microns)*	*Total root hair surface, by categories (sq. ft.)*
Main	53.25	3,481,463	1,000	2.16	15	1.73
Secondary	45.00	244,196,860	860	130.20	12	87.65
Tertiary	33.00	5,775,159,861	800	2,864.40	12	1,873.72
Quaternary	19.00	8,312,730,104	700	3,607.10	12	2,359.94
Totals		14,335,568,288		6,603.86		4,323.04

*[1] The number of root hairs on a root-length of 1 mm.

smallest but most numerous being on the quaternary roots. The calculated total root hair surface of the entire plant was 4,321 sq. ft. The value for roots plus root hairs was 6,875 sq. ft., which represents the potential soil contact surface of this single plant. The total exposed surface of the tops was estimated to be about 50 sq. ft., which is 0.073% of the root surface.

According to Wadleigh (1957) the particles in a cubic foot of loam soil have a total surface of about 560,000 sq. ft. Since the rye plant, studied by Dittmer, was grown in 1.9 cu. ft. of soil, the surface area of this amount of soil was 1,064,000 sq. ft. or 154 times that of the surface area of the roots that grew in the soil. The enormous root surface of the rye plant was, therefore, actually only two-thirds of one percent of the soil surface available for contact. This percentage may seem small, but the writer actually wonders how it can be so large since much of the soil surface is ordinarily inside of aggregates, or in clay lattices where the roots are unable to penetrate. Even if we assume that the soil was completely unaggregated, it is still difficult for the writer to account for the observed root surface–soil surface relationship.

Dittmer calculated that if the four months' growth had been evenly distributed over the entire period of the experiment, each day would have given new root hairs having a total length of nearly 55 miles, or for both roots and root hairs a daily addition of about 58 miles to the length of the subterranean parts of this one plant. Since there was little growth initially, the values for the later period must have been greater than the average values that include the seedling period.

Determinations of the extent of root development of oats, rye, and bluegrass under field conditions were subsequently made by Dittmer (1938). In this study core samples were taken to a depth of 6 inches and the number and length of the roots and root hairs measured. These data are given in Table 16.IV. Although the root development per unit volume of soil was less under these field conditions than in the greenhouse, the total for the three crops, especially of bluegrass, are very impressive.

Pavlychenko (1942) studied the root systems of crested wheatgrass (*Agropyron cristatum*), slender wheatgrass (*A. pauciflorum*), and smooth bromegrass (*Bromus inermis*). The number and length of the first, second, and third order roots from plants grown separately in the open under Canadian conditions were determined. The roots penetrated to a depth of 2–8 ft. and spread laterally to 3 ft. or more depending on soil type and moisture. The root lengths of mature plants, age 435 days, were as much as 147 miles per plant for smooth bromegrass, 178 miles for slender wheatgrass, and 360 miles for crested wheatgrass. Approximately 90–95% of the root elongation occurred during the second season.

Pavlychenko states that the extent of development of the fine root structures was amazing. Roots that were only about a tenth of a millimeter in diameter grew through hard soil to a distance of 185 cm or more, and each branch from the main roots developed 600–700 finer branches. One nodal root of crested wheatgrass together with its branches attained a total length of 17.7 miles. Data for root hairs were not reported.

The number of nodal roots per plant that developed under sod conditions was only about 1–3% as great as on spaced plants, and the length was greatly curtailed. The

TABLE 16.IV

NUMBER, LENGTH AND SURFACE AREA OF PLANT ROOTS GROWN UNDER FIELD CONDITIONS (from DITTMER, 1938)

Plant	*Roots**[1]			*Root hairs**[1]		
	number (thousands)	*total length (ft.)*	*total root surface (sq. ft.)*	*number (millions)*	*total length (miles)*	*total root surface (sq. ft.)*
Oats	96	3,056	7.1	128	100	75.4
Rye	129	4,278	11.0	255	204	167.1
Bluegrass	1,722	25,670	46.7	1051	652	344.3

*[1] Roots and root hairs per square foot to a depth of 6 inches.

quantity of underground material produced by the three grasses mentioned above, grown under sod conditions, was in the range of 1.5–2.2 tons per acre after two years, and up to 4.2 tons after 4 years.

In other studies Pavlychenko (1937) determined that when wild oats (*Avena fatua*) spring rye, and Marquis wheat were grown to maturity free from competition the total lengths of the entire root systems were 54.5, 49.1 and 44.2 miles, respectively. Close seeding or weed competition markedly reduced the extent of the root systems.

These data of Dittmer, and of Pavlychenko, serve to emphasize very dramatically the importance of roots in aggregate formation and in the overall build-up of an ideal soil structure that leads to good tilth and aeration, as well as to water-holding power and ready drainage. Roots themselves are major factors in producing the conditions that they themselves require.

Organic matter can under some conditions exert a marked effect on root growth through a dilution effect that does not necessarily involve aggregation as discussed here (Sprague and Marrero, 1931, 1932). This occurs commonly in greenhouse and in flower and vegetable garden soils, but only to a minor extent in field soils. The horticulturist who mixes comparatively large amounts of peat with soil for greenhouse use is using the peat largely in order to make a loose, well-aerated mixture that roots can penetrate without difficulty. The city gardener may add peat to his heavy clay subsoil for much the same purpose. In well-aggregated soils, as already stated, roots move readily through the non-capillary pore spaces that are larger than the roots. When such space development is poor, then organic matter, if added in sufficient amounts, can act as a substitute for the usual pore space. Such a mixture commonly offers even less resistance to root ramification than does the well-aggregated soil. Exfoliated vermiculite is often used as a partial substitute for peat in the preparation of potting mixtures, and with much success. Even a plow sole, natural hardpan, or other very compact soil, can be made more permeable to roots for a time at least if sufficient peat or similar material can be intimately incorporated with the soil, but of course this is rarely feasible.

Root growth through soil pores

A plentiful supply of organic matter, or humus, is one of the most essential requirements in most soils for an abundant and extensive production of finely-divided roots. And such an extensive and vigorously growing root system is, with few exceptions, an essential requirement for the higher levels of crop production. Many factors can affect the top–root ratio of a plant, but under reasonably normal soil and climatic conditions there is usually a close correlation between root growth and top growth of any given crop. If the soil environment is not favorable for root development the above-ground portions of the plant will suffer. The top must depend on the roots for mineral nutrients and water, and its growth is dependent upon how successful the roots are in furnishing the needed supplies.

The root system is a dynamic one that is affected markedly by the chemical, physical and biological conditions that prevail in soil. It also exerts its effect upon the soil and upon the organisms living in it. As a result of the removal of nutrients, plants may make the soil less suitable for crops that follow. On the other hand, root action and the release of organic matter that always occurs during growth and after death, often greatly improves the soil environment, especially physically.

Under suitable climatic and environmental conditions the requirements of roots for good development are for adequate pore space, good aeration, sufficient soil moisture, available nutrients, suitable pH and absence of inhibiting or toxic ions or compounds. Organic matter through its improvement of physical conditions, exchange capacity, nutrient content, chelation of minor elements, and buffering action plays a major role in assuring that soils meet these root requirements. As has been stated previously, it is in the permanent grasslands (chernozem soils) that the nearly perfect root environment is found.

A description of how grass or grass-legume roots work, given many years ago by Bradfield (1937), needs few changes now in the light of subsequent research. It is as follows: "For generations farmers have realized that for some reason cultivated crops grew better following such a mixture (grass plus legumes). Under grass most soils assume a granular or crumb structure. The exact mechanisms of the formation of these crumbs is not fully understood, but the result obtained is universally regarded by soil physicists as the ideal physical state for the growth of most crops. It is best developed in soils which are saturated with lime and which contain from 3 to 10% organic matter. Having these amounts of lime and organic matter in the soil, however, will not ensure a good granular structure. Something else is needed. The organic matter must be of the proper type and it must be properly distributed. I have tried to picture to myself how these granules might be formed and why they are so important. Additional evidence is needed, but I feel that the picture is reasonably accurate.

"Grass roots are so numerous that in a well-established sod they are seldom over 3 to 5 millimeters apart. These roots ramify the soil in all directions. Each root represents a center of water removal. As water is removed from the soil in contact with the root additional water moves toward the root by capillarity. As water is removed the pressure developed by the capillary forces, compressing the granule from all sides, is great, in many soils it reaches over 5,000 pounds per square inch. As a result these granules become quite dense, their apparent specific gravity ranging from 1.8 to 2.0. The total pore space inside them is small and the size of the pores is very small. Water moves into them slowly but is held firmly. The pores are so narrow that they are easily completely sealed by capillary water and as a result the ventilation of the interior is poor. Consequently, reducing conditions frequently exist on the interior of the granules simultaneously with oxidizing conditions on their surface. This often causes a migration of substances which are more soluble when in the reduced form to the surface of the granule where they are oxidized and deposited. This deposit serves as a cement and helps to stabilize the granule. Very hard granules of soil may be formed by the compression due to surface tension alone, but such granules are not water stable. When immersed in water, the air-water interface gradually disappears throughout and the granule breaks to pieces.

"In forcing its way through the soil many cells are sloughed off the living root and serve as food for bacteria. Eventually, the roots die and are decomposed in situ, forming a humified, often water-resistant coating around the granule. The marked difference in color between the surface of such granules and their interior is evidence of this. In many respects it seems to me these tiny granules may be compared to miniature 'earths'. Most of the inhabitants live near the surface where the 'air' is better. In the strongly granulated soil practically the entire mass of clay and silt particles are clumped together in these water-stable aggregates. As a result there are two fairly sharply defined groups of pores in such soils, capillary pores within the granule and non-capillary pores between the granules. The non-capillary pores are relatively large. Water enters them readily but is retained only at the periphery. This leaves a continuous series of connecting chambers through which air can readily pass. The water at the periphery is drawn into the capillary pores between the unit particles making up the granules. This water constitutes the most closely held reserve in the soil. Such a soil has a permeability approaching that of sandy soils combined with a storage capacity of the heavier textured soils.

"Such are the structures which perennial grasses tend to develop in soils. Such soils provide optimum growing conditions for most crops. The organic matter constitutes a good reserve of the elements essential for growth. Water and air are present in the proper proportions. With an abundance of food, water, and air, soil micro-organisms flourish and gradually convert the organic reserves into the simpler forms required by crop plants.

"Crop roots can easily force their way through the large well-aerated non-capillary pores. As a result, a more efficient and extensive absorbing system is developed. The food reserves are concentrated largely on the surfaces of these pores. Once a soil is well granulated and when well-aerated interfaces are formed, roots will tend to follow them instead of forcing their way through the dense aggregates. The effect of the roots is thus accumulative. It is not definitely known how many seasons' growth are required to produce the optimum structure. The major part of the work is probably done in the first few years of growth of the sod."

Bradfield's description of how roots grow and help to form aggregates is an excellent one. Since this was written, our knowledge of the importance of the microorganisms in the rhizosphere and the gums that they produce has been greatly extended. We need to add this newer information to the picture that he presented. Emerson's model of an aggregate (Fig.16.2) shows how the bacterial gums serve as cements to hold the individual particles in water-stable aggregates. It is noteworthy that Bradfield, at such an early date, realized the importance of clay skins, although he did not refer to them in these terms.

CONDITIONS MOST FAVORABLE FOR AGGREGATION, TILTH AND ROOT EXTENSION

Much information has been published in recent years that goes far toward explaining why certain agricultural practices lead to unexpectedly poor soil aggregation whereas others produce surprisingly good results. Most of this information is presented above but in a somewhat disconnected way as the various factors involved are discussed individually. When these facts are assembled and evaluated what are the conditions that favor maximum aggregation and are at the same time economically feasible in soils of humid regions?

It is stated above that the best aggregated soils are those that have been continually in grass for many years. It follows, then, that if we thoroughly understand what is taking place in grass sods we know the chief conditions that are responsible for good aggregation. In my opinion this excellent aggregating effect of plants may be attributed to the existence *simultaneously* of nearly ideal conditions for aggregate formation and aggregate stabilization. This unique situation seldom exists elsewhere under natural conditions in the absence of crops. It is obvious that as aggregates are formed they must be quickly stabilized or else they will tend to disintegrate almost as fast as they are formed.

As stated previously, the roots of grasses are so finely divided and extensive that they reach within a few millimeters or microns of most of the soil particles in the dense sod in which they grow. These roots exert ever-varying pressures and remove water locally and non-uniformly, thus making conditions ideal for aggregate formation. While this is happening the roots are also constantly secreting, excreting and discarding organic substances, including root cells, that the mass of rhizosphere microorganisms immediately utilize as energy sources. They convert these in part into microbial gums that are ideal substances for the binding together of soil particles.

In the absence of cultivation, the aggregates, once formed, tend to resist the forces that would destroy them. A part of this resistance is attributable to the presence of iron and aluminum oxides, carbonates and amorphous silica. Furthermore, clay skins, or cutans, which form in undisturbed soils and root channels, help materially in stabilizing the aggregates. Brewer (1960) expressed the opinion that cutans may have a very considerable effect on profile development and plant growth and they may dominate the characteristics of the soil material. Even when cutans are very thin and comprise only a small proportion of the soil material, their large surface area per unit volume of soil makes them an important factor in various aspects of soil behavior. The protective film tends to isolate the soil from processes such as leaching and it no longer acts as a fully porous medium. Normal movement and rearrangement of the soil particles, which would greatly affect aggregation, is curtailed or markedly modified. The effect of the cutans in stabilization increases with time due in part to their continued increase in thickness. Their effect is also dependent on the nature of the ingredients that make up the coatings and on the distribution of the cutans in the soil material.

Chemical studies have yielded results that are in harmony with the ideas expressed above. These have involved the use of oxidizing agents, chiefly sodium periodate, for the destruction of polysaccharides in soils. In such studies, any decrease in aggregate stability following periodate treatment should be a measure of the contribution of polysaccharides to this stability. From such work Mehta et al. (1960) concluded that polysaccharides are not the sole agents responsible for natural aggregation. Greenland et al. (1962) in similar studies observed that aggregate stability in cropped soils and those under young pastures was primarily due to polysaccharides or polyuronides. In soils from old pastures, or those that contained free calcium carbonate, other materials were involved in stabilization. Harris et al. (1963), using artificial aggregates, reported that sodium periodate caused only a 50% reduction in stability. The contribution of polysaccharides to stability depended on soil composition. Clapp and Emerson (1965) found that calcium carbonate in soils interferes with the oxidation of polysaccharides, thus explaining some of the results mentioned above. They concluded that there appears to be two types of polymeric organic materials binding the grassland crumbs, one extractable by pyrophosphate and the other oxidizable by periodate. Surface crumbs from wooded sites on the same soils were very resistant to all treatments. Periodate alone destroyed the stability of cultivated crumbs.

These chemical studies not only confirm long-time observations that permanent grasslands and some woodlands have especially stable aggregates, but show that the stability is not due to polysaccharides alone. Undoubtedly inorganic as well as organic substances play an important role, and doubtless both types of materials are exerting their effect to a large extent through their presence in clay skin formations.

Under ordinary farming conditions there are many conditions where aggregate formation is favored but where there may be inadequate readily available organic materials present throughout the soil for abundant microbial development. Polysaccharide formation is then limited and stabilization unsatisfactory. In other cases large quantities of crop residues and other forms of available energy materials may be turned under with disappointing effects on aggregation. These materials cannot be expected to be very effective in this respect, for their primary effect is on aggregate stabilization and not on aggregate formation. Crop residues, other than residual roots, and animal manures are also seldom intimately mixed with the soil and any microbial gums formed are likely to be localized and not be everywhere that they are needed. It is surprising that there has not been more emphasis on the necessity for providing simultaneously for both aggregate formation and stabilization. This necessity is certainly obvious, even though it is usually overlooked.

REFERENCES

Allison, F.E., 1947. *Soil Sci.*, 63: 439–450.
Allison, F.E., 1968. *Soil Sci.*, 106: 136–143.
Barber, S.A., 1959. *Soil Sci. Soc. Am. Proc.*, 23: 258–259.
Barley, K.P., 1959a. *Aust. J. Agric. Res.*, 10: 171–178.
Barley, K.P., 1959b. *Aust. J. Agric. Res.*, 10: 371–376.
Barley, K.P. and Greacen, E.L., 1967. *Adv. Agron.*, 19: 1–43.
Barrows, H.L., Simpson, E.C. and Tu, H.Y., 1966. *Soil Sci. Soc. Am., Proc.*, 30: 317–320.
Benoit, R.E., Willits, N.A. and Hanna, W.J., 1962. *Agron. J.*, 54: 419–420.
Bernier, B., 1958. *Can. J. Microbiol.*, 4: 195–204.
Bisal, F. and Nielsen, K.F., 1967. *Soil Sci.*, 104: 268–272.
Bradfield, R., 1937. *J. Am. Soc. Agron.*, 29: 85–92.
Brewer, R., 1960. *J. Soil Sci.*, 11: 280–292.

Brouwer, R., 1965. *Proc. Easter School Agric. Sci., Univ. Nottingham, 12th, Nottingham*, pp.152–166.

Browning, G.M. and Milam, F.M., 1944. *Soil Sci.*, 57: 91–106.

Buol, S.W. and Hole, F.D., 1959. *Soil Sci. Soc. Am., Proc.*, 23: 239–241.

Buol, S.W. and Hole, F.D., 1961. *Soil Sci. Soc. Am., Proc.*, 25: 377–379.

Cagauan, B. and Uehara, G., 1965. *Soil Sci. Soc. Am., Proc.*, 29: 198–200.

Chesters, G., Attoe, O.J. and Allen, O.N., 1957. *Soil Sci. Soc. Am., Proc.*, 21: 272–277.

Clapp, C.E. and Emerson, W.W., 1965. *Soil Sci. Soc. Am., Proc.*, 29: 127–134.

Dittmer, H.J., 1937. *Am. J. Bot.*, 24: 417–420.

Dittmer, H.J., 1938. *Science*, 88: 482.

Edwards, A.P. and Bremner, J.M., 1967a. *J. Soil Sci.*, 18: 47–63.

Edwards, A.P. and Bremner, J.M., 1967b. *J. Soil Sci.*, 18: 64–73.

Edwards, C.A. and Heath, G.W., 1963. In: J. Doeksen and J. Van der Drift (Editors), *Soil Organisms.* North-Holland, Amsterdam, pp.76–84.

Emerson, W.W., 1954. *Trans. Int. Congr. Soil Sci., Leopoldville, 5th, 1954*, 2: 65–68.

Emerson, W.W., 1959. *J. Soil Sci.*, 10: 235–244.

Emerson, W.W., 1960. *Nature*, 186: 573–574.

Evans, A.C., 1948. *Ann. Appl. Biol.*, 35: 1–13.

Fieldes, M., 1962. *Trans. Jt. Meet. Comm. IV, V, Int. Soc. Soil Sci. N.Z.*, pp. 62–78.

Filippovich, Z.S., 1956. *Pochvovedenie*, 2: 16–26. Abstr. In: *Soils Fert.*, 19: 333.

Forsyth, W.G.C. and Webley, D.M., 1949. *J. Gen. Microbiol.*, 3: 395–399.

Gieseking, J.E., 1949. *Adv. Agron.*, 1: 159–204.

Goedewaagen, M.A.J. and Schuurman, J.J., 1950. *Landbouwkd. Tijdschr.*, 62: 469–482.

Greenland, D.J., 1965a. *Soils Fert.*, 28: 415–425.

Greenland, D.J., 1965b. *Soils Fert.*, 28: 521–532.

Greenland, D.J., Lindstrom, G.R. and Quirk, J.P., 1962. *Soil Sci. Soc. Am., Proc.*, 26: 366–371.

Guild, W.J.M., 1955. In: D.K.M. Kevan (Editor), *Soil Zoology.* pp.83–98.

Harris, R.F., Allen, O.N., Chesters, G. and Attoe, O.J., 1963. *Soil Sci. Soc. Am., Proc.*, 27: 542–545.

Harris, R.F., Chesters, G., Allen, O.N. and Attoe, O.J., 1964. *Soil Sci. Soc. Am., Proc.*, 28: 529–532.

Harris, R.F., Chesters, G. and Allen, O.N., 1966. *Adv. Agron.*, 18: 107–169.

Hendricks, S.B., Cady, J.G. and Flach, K.W., 1962. *Trans. Jt. Meet. Comm. IV, V, Int. Soc. Soil Sci., N.Z.*, pp. 34–38.

Hoeksema, K.J. and Jongerius, A., 1959. *Meded. Landbouwhogesch. Opzoekingsstn. Staat Gent*, 24: 188–194.

Jacks, G.V., 1963. *Soils Fert.*, 26: 147–150.

Keefer, R.F. and Mortensen, J.L., 1963. *Soil Sci. Soc. Am., Proc.*, 27: 156–160.

Khalifa, E.M. and Buol, S.W., 1968. *Soil Sci. Soc. Am., Proc.*, 32: 857–861.

Khalifa, E.M. and Buol, S.W., 1969. *Soil Sci. Soc. Am., Proc.*, 33: 102–105.

Kroth, E.M. and Page, J.B., 1947. *Soil Sci. Soc. Am., Proc.*, 11: 27–34.

Laird, A.S., 1930. *Univ. Fla. Bull.*, 211: 1–27.

Logsdail, D.E. and Webber, L.R., 1959. *Can. J. Soil Sci.*, 39: 103–106.

Low, A.J., 1955. *J. Soil Sci.*, 6: 179–199.

Lutz, J.F., 1936. *Soil Sci. Soc. Am., Proc.*, 1: 43–45.

McCalla, T.M., 1951. *Soil Sci. Soc. Am., Proc.*, 15: 182–186.

McCalla, T.M., Haskins, F.A. and Frolik, E.F., 1957. *Soil Sci.*, 84: 155-161.

McIntyre, D.S., 1956. *J. Soil Sci.*, 7: 302–306.

Marshall, T.J., 1959. *Commonwealth Bur. Soil Sci., G.B., Tech. Commun.*, 50: 1–88.

Marshall, T.J., 1962. *Trans. Jt. Meet. Comm. IV, V, Int. Soc. Soil Sci., N.Z.*, pp. 243–257.

Martin, J.P., 1945a. *Soil Sci.*, 59: 163–174.

Martin, J.P., 1945b. *J. Bacteriol.*, 50: 349–360.

Martin, J.P., 1946. *Soil Sci.*, 61: 157–166.

Martin, J.P., Martin, W.P., Page, J.B., Raney, W.A. and De Ment, J.D., 1955. *Adv. Agron.*, 7: 1–37.

Martin, J.P., Ervin, J.O. and Shepherd, R.A., 1965. *Soil Sci. Soc. Am., Proc.*, 29: 397–400.

Martin, J.P., Ervin, J.O. and Shepherd, R.A., 1966. *Soil Sci. Soc. Am., Proc.*, 30: 196–200.

Martin, W.S., 1944. *Empire J. Exper. Agric.*, 12: 21–32.
Mazurak, A.P. and Ramig, R.E., 1963. *Soil Sci. Soc. Am., Proc.*, 27: 592–595.
Mehta, N.C., Streuli, H., Müller, M. and Deuel, H., 1960. *J. Sci. Food Agric.*, 11: 40–47.
Mehta, N.C., Dubach, P. and Deuel, H., 1961. *Adv. Carbohydr. Chem.*, 16: 335–355.
Neal, O.R., 1953. *Adv. Agron.*, 5: 383–406.
Nye, P.H. and Greenland, D.J., 1960. *Commonwealth Bur. Soil Sci., G.B. Tech. Commun.*, 51: 1–156.
Oswalt, D.L., Bertrand, A.R. and Teel, M.R., 1959. *Soil Sci. Soc. Am., Proc.*, 23: 228–230.
Page, J.B., 1954. *Soil Microbiol. Conf., Purdue Univ. Lafayette, Ind.*
Pavlychenko, T.K., 1937. *Ecology*, 18: 62–79.
Pavlychenko, T.K., 1942. *Can. Natl. Res. Counc. Can.*, 1088: 1–46.
Pearson, R.W., 1966. In: W.H. Pierre, D. Kirkham, J. Pesek, and R. Shaw (Editors), *Plant Environment and Efficient Water Use.* Am. Soc. Agron. and Soil Soc. Am., Madison, Wisc., pp. 45–126.
Pinck, L.A., Dyal, R.S. and Allison, F.E., 1954. *Soil Sci.*, 78: 109–118.
Quastel, J.H., 1952. *Soil Sci.*, 73: 419–426.
Quastel, J.H., 1954. *Ann. Rev. Plant Physiol.*, 5: 75–92.
Rogowski, A.S. and Kirkham, D., 1962. *Soil Sci. Soc. Am., Proc.*, 26: 213–216.
Rovira, A.D. and Greacen, E.L., 1957. *Aust. J. Agric. Res.*, 8: 659–673.
Russell, E.W., 1938. *Imp. Bur. Soil Sci., Tech. Commun.*, 37: 1–40.
Sivarajasingham, S., Alexander, L.T., Cady, J.G. and Cline, M.G., 1962. *Adv. Agron.*, 14: 1–60.
Sprague, H.B. and Marrero, J.F., 1931. *Soil Sci.*, 32: 35–49.
Sprague, H.B. and Marrero, J.F., 1932. *Soil Sci.*, 34: 197–208.
Stallings, J.H., 1952. *U.S. Dep. Agric., SCS-TP-110*: 1–23.
Ten Eyck, A.M., 1899. *N.D. Agric. Exper. Stn. Bull.*, 36: 332–362.
Ten Eyck, A.M., 1900. *N.D. Agric. Exper. Stn. Bull.*, 43: 535–560.
Ten Eyck, A.M., 1905. *Kans. Agric. Exper. Stn. Bull.*, 127: 199–252.
Teotia, S.P., Duley, F.L. and McCalla, T.M., 1950. *Nebr. Agric. Exper. Stn. Res. Bull.*, 165: 1–20.
Uehara, G., Flach, K.W. and Sherman, G.D., 1962. *Trans. Jt. Meet. Comm. IV, V, Int. Soc. Soil Sci. N.Z.*, pp.264–269.
Wadleigh, C.H., 1957. In: *Soil – The Yearbook of Agriculture 1957.* U.S. Dep. Agric. U.S. Govt. Printing Office, Washington, D.C., pp.38–49.
Weaver, J.E., 1926. *Root Development of Field Crops.* McGraw-Hill, New York, N.Y., 291 pp.

Chapter 17

A FACTOR IN WATER CONSERVATION AND EFFICIENCY OF USE

INTRODUCTION

A supply of available water in the soil for the use of growing crops as they need it is one of the most important factors in agriculture. Often it is the one factor that determines whether there will be any crop.

Organic matter on or in the soil cannot of course act as a substitute for water, but under many conditions it can go a long way toward assuring that the best use will be made of the water that reaches the soil, either in the form of rain or through irrigation.

Organic matter, including both humus and plant residues, may exert its effects in a number of ways, but chiefly through improved infiltration, decreased loss via evaporation, better drainage of fine-textured soils, more extensive and deeper root systems that make more moisture available for crop use, and increased yields that result in more harvested crop per unit of water lost by evapotranspiration. The extent to which organic matter acts in these various roles varies widely with soil, climate, and crop grown, but it is seldom that organic matter does not produce beneficial effects in one or more of the above categories. If additions of commercial fertilizers are made, some of the beneficial effects of organic matter may be increased. Fertilizers and organic matter commonly work together, one being complementary to the other.

The amount of water required to produce a crop of corn under normal conditions is only about 6–8.5 inches (Bertrand, 1965), although the annual rainfall may be 30–50 inches. This emphasizes the inefficiency with which this water is utilized in agriculture. The water not used by the crop is lost through runoff, deep percolation, and evaporation. The lower the annual rainfall the more important is the loss by evaporation from the soil surface.

INFILTRATION

Rains occur at irregular intervals, in widely varying amounts, and there are few places where an adequate amount of moisture is available at all times for the optimum growth of crops. An efficient agriculture is, therefore, usually dependent in a major way upon careful conservation of the water that is available, especially during the weeks immediately preceding and during the crop growing season. The better soils act as effective storage reservoirs for the rainfall, but only if conditions are such that the water can enter at such a rate as to minimize runoff. If the slope is too steep it is often impossible to capture all of the rainfall before it escapes, except by altering the slope by engineering methods. In soils of more moderate slope, however, organic matter, both living and dead, can serve effectively in aiding to catch the rainfall before being lost as runoff.

For a more complete discussion than can be given here of the factors that influence infiltration rates and permeability of soils, reference should be made to the publication by Parr and Bertrand (1960). They also describe methods used for measuring infiltration and discuss the theoretical considerations involved.

In the Southern Piedmont area of the United States, where the annual rainfall averages about 50 inches, it has been estimated that about 11 inches of this is lost as runoff. Fortunately, a considerable portion of this loss occurs during the season when crop growth, if any, is at a minimum, and when the soil is already at field capacity. Under these conditions, if runoff could be prevented, most of the water so captured would merely percolate through the soil to the groundwater.

Wischmeier and Mannering (1965) reported that the runoff from cropped plots in various studies conducted in 24 states ranged from 3–36% of total precipitation. Increasing the content of decomposed and partially decomposed organic residues substantially increased infiltration into most soils.

Organic matter increases infiltration by helping to hold water on the soil surface long enough for it to seep into the soil, and by improving the physical conditions of the soil so that less time is required for it to move through the soil into the root zone. It is at the soil surface that most of the problems connected with infiltration arise. When a fine-textured soil is left bare the raindrop impact at the surface destroys most of the surface soil aggregates, and when it dries crust formation is the result. The rate of water penetration through such crusts is often only a fraction of what it would be if the soil aggregates were left undisturbed.

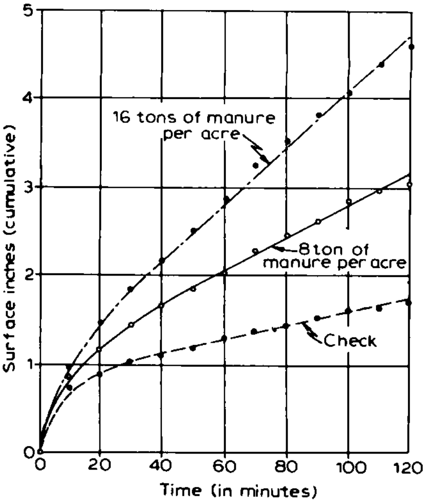

Fig.17.1. Infiltration capacity in surface inches in Clarion loam as affected by manure. (From Smith et al., 1937.)

Fig.17.1, taken from Smith et al. (1937) shows that an 8-ton application of manure to a Clarion loam increased infiltration over a 2-hour period by nearly 85%, whereas a 16-ton addition produced twice this increase over the check.

Tackett and Pearson (1965) compared the effect of simulated rainfall and mechanical compaction of soil on surface crust formation and water permeability. Crusts formed under simulated rainfall were very dense and had a thin skin of well-oriented clay. Mechanical pressure did not produce this surface effect. Water permeability of soil underlying the crusts was about 5 times that of the surface. In compacted soils permeability of the surface and underlying materials was the same.

Crusts that form subsequent to rains serve to retard evaporation much more than crusts that may develop after flooding (Bresler and Kemper, 1970). The destructive effect of the raindrop impact is the apparent reason for the difference (see Chapter 27). In the region immediately below the crust there is a high resistance to the flow of water upward, which hastens the formation of a surface dry layer and reduces evaporation.

A complete plant cover on the soil serves to break the impact of the raindrops and keeps the soil open and porous. A grass sod is an example of such an ideal protection, but in growing cultivated crops such a condition exists at best for only a portion of the season, because the land is necessarily bare or partly so for a considerable period after plowing and seeding, and possibly also after harvesting. Even during the growing period all of the soil surface is seldom protected from the energy of falling raindrops.

An organic mulch also protects the soil against crust formation, but aside from the scarcity of mulching materials and costs, the use of mulches presents other problems that are discussed in detail in Chapter 25. Many types of mulches, if properly managed (Army et al., 1961), are very effective in minimizing runoff. Plant residues on the surface also markedly decrease the rate of drying of soil in the surface half-inch layer, but under field conditions Army et al. observed that the soil moisture content below 2 inches was not materially increased by surface residues.

Organic matter mixed with the soil also aids greatly in increasing infiltration by helping to provide better aggregation and structure, and consequently lower bulk density and increased ease of water movement. Wischmeier and Mannering (1965), for example, found that soils with high yields of corn and correspondingly large quantities of residues had less runoff than plots with low yields. Moderate to heavy amounts of residue material incorporated into the soil at each plowing over a period of years were more effective than an increase in canopy for improving infiltration. Runoff from these heavily cropped soils, where residues were returned, averaged only 51% of that from fallow soils, even though corn provided little surface cover during the early growth period. These workers state that a single application of straw or cornstalks plowed under in the spring had little effect on infiltration during the year. Increased infiltration was the result of gradual distribution of the organic matter throughout the plow layer by successive annual additions and plowings. As the plant materials decayed and were thoroughly mixed with the plowed layer over the years, the beneficial results on infiltration became very marked.

Using a rainulator in studies in Indiana with 44 different soils, mostly silt loams or

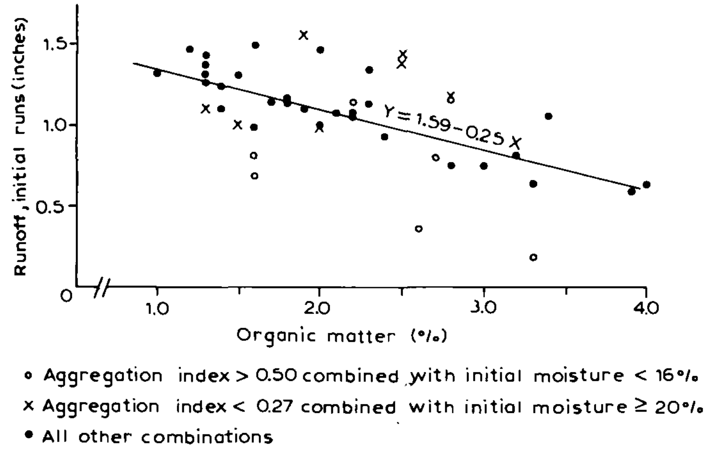

Fig.17.2. Relation of runoff to organic matter content (2.5 inches of rain in 1 hour). (From Wischmeier and Mannering, 1965.)

loams, Wischmeier and Mannering (1965) observed that organic matter content of the soil was the measured variable most closely correlated with runoff. In linear regression analyses, organic matter accounted for 36% of the total runoff variance for the initial 2.5-inch rains and 43% for wet runs. Fig.17.2 shows the regression curve for the initial runs.

WATER RETENTION

The amount of water that can be retained by a soil within the root zone is dependent chiefly upon the characteristics of the soil and on its depth. Many podzols, for example, are rather compact and often have a hardpan or near hardpan at plow depth or possibly a little lower. Others have only a comparatively shallow surface layer with parent rock at a depth of a foot or two. The total water that such a soil can hold may be no more than 2–3 acre inches and frequently less. In contrast, the chernozem soil is often fairly uniform to a depth of 6–10 ft. and has a good physical condition due chiefly to its high content of organic matter. Having been formed over centuries under a cover of grass and with limited rainfall, there is little stratification, aggregation is excellent, and deep root penetration is favored. Such a soil has maximum capacity for water retention but this holding capacity may never be used fully because the soil normally exists in a region of limited rainfall.

Most of the sun's energy that reaches the earth in the form of light is used in the evaporation of water. If the rays impinge on a free water surface such as a lake, as much as about 0.3 inches of water may be evaporated per day during hot summer months. A like amount may also be lost from a wet soil if the surface is kept moist. At any given time under these conditions, if wind velocity is at a minimum, the loss is correlated directly with light intensity, which in turn affects the temperature.

Under normal field conditions, however, the evaporation from a soil surface is seldom as great as from a free water one, because the soil is protected from the sun's rays by a vegetative cover of both living plants and any dead organic residues that may accumulate on the soil surface. Furthermore, the surface inch of soil does not long remain saturated or even at field capacity. Soon after a rain much or most of the water in this surface inch of soil either moves to lower levels or is evaporated. The remaining layer of dry soil then serves to insulate the moist soil below, and fortunately water from the lower portions of the horizon moves into the surface at such a slow rate that it is commonly almost negligible. The sun's rays that hit this dry layer then serve to raise the temperature to a considerable extent, but most of the energy is reflected into the atmosphere. Where heavy vegetation is present little of the energy reaches the soil but is either absorbed by the growing crop and used in transpiration or is carried away in the air by advection.

From the standpoint of water conservation, the main aim should be to minimize evaporation losses from the soil surface, thus leaving as much as possible of the soil moisture for the use of the crop. In recent years much research (see Pierre et al., 1965) has been conducted in attempts to reduce evaporation from soils and lakes by means of chemicals. Hexadecanol, for example, suppresses the evaporation of water from either a free-water surface or from soil. Olsen et al. (1964) observed that this chemical decreased water loss from a loam soil 43% during a 10-day period. A portion of the data is shown in Fig.17.3. A surface placement was most effective, remaining unchanged during a 14-month test period. They state that hexadecanol allows the surface soil to dry and thus creates a diffusion barrier to water loss by vapor transfer. It also increases the rate of water infiltration.

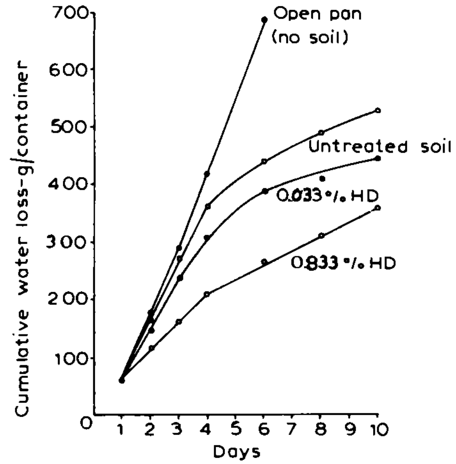

Fig.17.3. Comparison of cumulative water losses by evaporation from an open pan (no soil) and from untreated soil with loss from hexadecanol-treated soil, in relation to time. (From Olsen et al., 1964.)

AVAILABLE MOISTURE SUPPLY

The supply of available moisture to plants in a soil, considered in a broad sense is, according to Jamison (1956), the total quantity that can be extracted from the profile during growth. In this broad sense the factors include those involving the plant, climate, and soil. He lists the plant factors as drought resistance, rooting depth and ramification, plant vigor, and growth stage. The climatic factors are evaporation and transpiration losses as influenced by air temperature, air humidity, fog, wind, and sunlight. Soil factors are moisture tension relationships and osmotic pressure of the soil solutions; ions in the soil solution and absorbed on the colloids; and soil moisture conductivity relationships, including wetting depth, soil temperature, and temperature gradients. As stated above, soil texture and characteristics, and depth of the profile, should also be listed since they are very important.

Jamison showed that, except for sandy soils, organic matter increases did not increase the capacity of a soil to store available water. This is primarily because much of the water held in organic materials is held so tightly that it is unavailable to plants. Furthermore, the amount held per unit volume is not so great as weight percentage values would indicate. Even in sandy soils the addition of organic matter has only a small effect on available moisture. The tenacity with which organic matter holds moisture in an unavailable state has been emphasized repeatedly by those who have worked with peats.

Organic matter that improves soil aggregation and aeration and decreases bulk density usually has little effect on moisture storage capacity. Aggregation commonly increases the volume of large pores but reduces the volume of pores that store moisture. However, the improvement in soil structure and aeration of fine-textured soils has such a favorable effect on root growth that the roots ramify into a larger volume of soil, and thereby secure much more moisture for the crop than they could otherwise obtain.

DRAINAGE

The effective use of water in crop production requires that the crop should not only have adequate water but should also not have an excess of it. In other words the water must be able to move through a soil with such speed that the spaces between aggregates or particles do not long remain filled with it. In low-lying lands either open ditches or tile drains are necessary for removal of excess water, but except in very sandy soils this may not be adequate. In addition, the aggregation and structure of the soil need to be improved, and this is favored by organic matter additions. The addition of crop residues will have some effect but deep-rooted crops and grasses, if they can be made to grow, are likely to be more effective. As emphasized in previous chapters, there is no better way to improve aggregation and tilth than by the growing of grasses.

There is a close interrelation between the amount of water in a clay soil and oxygen supply. This is obvious, for the portion of the water in a soil that is free to move occupies the same space that air would occupy in the absence of this excess water. In the case of most of our common field crops if the roots are deprived of air for a day or so they will be severely and permanently damaged, if not killed outright. The rate of diffusion of oxygen through air is about 10^4 times greater than through water, which emphasizes the extreme need for good drainage.

Many low-lying soils, although fertile, constitute problem soils even after tile drainage has been provided. Most of these soils are fine-textured and after being nearly saturated with water for centuries they are so compact that the environment is not suitable for root proliferation of most crops. In addition, long submergence has often resulted in the production of toxic amounts of aluminum and reduced constituents, especially in acid soils (Foy and Brown, 1963, 1964). The conversion of such a soil into one that is suitable for general farm crops is often a slow process. Following drainage, and liming and fertilization as needed, soil tilth can usually be improved by cropping to fine-rooted crops that can tolerate the unfavorable conditions. As fresh organic matter is incorporated into the soil, bulk density is gradually decreased and the improved aeration and tilth will eventually permit the growth of deeper rooted crops. As the roots decay, the channels left provide better aeration and the roots serve as food for earthworms. Gradually soil aggregation is improved and the environment becomes suitable for a variety of crops.

Organic matter obviously plays a key role in the efficient use of water in crop production, even where water is often in excess. By its effects in bringing about better soil aggregation and aeration, and increased root proliferation, it may mean the difference between a good crop and an unprofitable one, or none.

UTILIZATION OF SOIL WATER BY PLANTS

Not all of the water that is held by soils against the force of gravity is available for use by plants. This is because: (1) at high levels of moisture stress, plants are unable to utilize all of the moisture that is present; and (2) much of the soil water is not in the immediate vicinity of plant roots.

Different kinds of plants vary somewhat in their ability to extract water from a dry soil, but these differences are not great. Plant tolerance of drought conditions is a much more important factor. Another important factor in the utilization of soil water is the matter of where the water is located. In soils having moisture contents of less than field capacity water movement is much too slow to meet the requirements of plants that are transpiring rapidly. The rate of capillary movement of water through soils, either horizontally or vertically, is much less rapid than many have supposed. Since the water cannot move readily toward the roots, it is necessary that the roots ramify throughout the soil if the soil water is to be used fully. Water in a reservoir moves readily, but water in soil that is held by capillarity is largely immobile.

The speed and extent to which roots can grow under ideal conditions was discussed in Chapter 16. Dittmer (1937), for example, found that the daily addition of roots plus root hairs to a single rye plant grown in the greenhouse was about 58 miles per day. Although this is probably near a maximum value, there would seem to be little doubt that many plants that normally have deep root systems have the ability to proliferate to such an extent that most of the soil water within the root zone becomes available to the crop, if root development is not impeded directly or indirectly by unfavorable soil conditions. Among the factors that oppose root extension are inadequate soil depth, soil compaction, hardpans, poor tilth and aeration, deficient nutrients, soil acidity and toxic substances. An abundant supply of organic matter, together with fertilizers and lime as needed, are often the major factors in assuring root proliferation, and hence effective use of the moisture in the soil reservoir. Organic matter functions through its effect in increasing soil aggregation, in reducing bulk density, and in supplying available nutrients needed for root growth. It also acts as a buffer and neutralizer of growth-inhibiting substances.

Although soil organic matter is a major factor in root proliferation, it is well to bear in mind that it is a source of food for microorganisms that compete with plant roots for oxygen. There is some research that indicates that this competition by the microflora can interfere with root growth. This can be true under rather extreme conditions but is usually not a very important factor under normal ones.

Extremely active growths of microorganisms with accompanying high oxygen demands occur when fresh undecomposed plant materials are added to soils, and occasionally seedlings are injured but usually for reasons other than lack of oxygen or excess carbon dioxide. Plant materials are ordinarily applied to the surface six inches of soil only, where aeration is usually not a problem except in very heavy soils and during periods of heavy rainfall. The process of adding these organic materials loosens the soil and improves aeration, and the bulky fresh organic materials keep the soil loose. Air diffuses into the soil very rapidly under these conditions. In warm, moist soils the period of extremely rapid decay lasts for only 3–6 weeks; the rate of decay falls off rapidly after about three weeks. While this is happening, the roots at a depth of perhaps 2–5 ft. or more are usually little affected by any oxygen demands by the microflora in the plowed layer, and little of the added organic matter reaches them. The growth of the plants is stimulated, however, and the more extensive root systems remain where they were formed and serve to improve growth conditions for succeeding crops. A little of the organic matter of the plowed layer may be carried to lower levels in some soils but for the most part the roots that are formed in the subsoil constitute the main source of organic matter for this region. If surface organic matter is carried down to the subsoil it would have little effect on oxygen consumption because it would be thoroughly decomposed long before it reached the lower levels. Much of the humus, as already emphasized, occurs as large, comparatively inert molecules that help to keep the soil well ventilated and loose. It would not act as an appreciable consumer of oxygen.

In medium- and fine-textured soils it is known that as roots grow through soil they are likely to be impeded markedly if the soil particles are dispersed. If the soil is well aggregated, however, the roots move with ease through the air spaces between aggregates. Organic matter helps markedly in providing a suitable soil structure, both by binding soil particles into aggregates by means of polysaccharides, and by weakening the pull between aggregates where stable forms of humus are predominant. By making soil conditions suitable for root proliferation it also aids in uptake and efficient utilization of water.

WATER VOLATILIZATION AND TRANSPIRATION

Soils lose water by both evaporation and transpiration, but the relative magnitude of the two processes depends upon the relative wetness of the surface. Peters and Russell (1959) and Peters (1960) found that where frequent summer showers occurred as much as 50% of the total water loss was via evaporation. When the surface soil is not kept wet most of the time, transpiration may be considerably greater than evaporation.

When water is stored in a reservoir and the wind velocity is near zero, the loss of water by evaporation is directly proportional to the amount of heat in the form of sunlight that impinges on the surface at any given time. If the water surface area is small, and the wind is blowing, some additional heat may reach the water via advection currents. In this case if heat from surrounding areas is actually absorbed by the water then the loss by evaporation may be somewhat greater than would occur where direct sunlight is the only source of heat. Heat energy from whatever source is the factor that raises the water temperature and brings about evaporation.

Essentially the same situation exists when the sun's rays strike the surface of an uncropped soil that is wet to field capacity including the soil surface. The evaporation is then the same as, or only very slightly less, than from a free water surface. But this is true for only as long as water is not limiting.

In a soil that is completely covered with green vegetation, and where moisture is not limiting, the loss of water by evapotranspiration is closely correlated with the intensity of the sun's rays, just as evaporation is correlated with heat absorption by a free water surface. The volatilization of water is much the same under the two conditions (Tanner and Lemon, 1962). A system of nonlimiting moisture in this case means that the roots of the crop are so located with respect to the water supply that the plants have all of the water that they can utilize. The soil need not be at field capacity if the roots are long enough to reach the water, wherever it may be, and can supply the tops with as much as they can utilize.

Under practical conditions it is only rarely that a soil is completely covered with green vegetation. At times between harvesting one crop and seeding the next, the soil may have little or no living plant cover. Even after the crop is well developed, some of the sun's rays penetrate through the plant cover and strike the soil directly. Under such conditions the loss of water is not much, if any, less than from an open water surface if water is not limiting and no dry soil crust develops.

In a cropped field soil it is seldom that water is nonlimiting, except for short periods. Plants commonly wilt during hot summer days and a crust soon forms at the soil surface. Under such conditions the loss of water is often considerably below the possible maximum based on the heat derived from the sun's rays. The heat not used in the evaporation of water is largely reflected and carried away by winds.

Under conditions of nonlimiting water, and where the soil is completely covered with green vegetation, the loss of moisture by evapotranspiration is largely independent of the size of the plants on it if heat is not brought in from other areas. Under these conditions a mowed lawn may lose as much water as similar grass that is three or four feet high. Actually, this situation is almost non-existent in the field, because some wind is always blowing and hot winds can markedly increase evapotranspiration from areas over which they pass. The taller the crop, the more likely that it will intercept heat from hot winds.

The effect of heat from surrounding areas is often noted to an extreme degree where very small plots are used. In the case of lysimeters, for example, plants are ordinarily grown on areas of 1–15 sq. ft. The area between these lysimeters may be much larger than the total cropped areas, and perhaps surfaced with sand or gravel. Under such conditions the reflected light and the heat that reaches the growing plants by advection greatly increases the loss of moisture from the crop. If the plants are tall-growing and spreading, the loss of moisture is especially great.

In practice, root length and degree of branching are also major factors in water loss because most of the water loss from cropped soils is via transpiration. Root length often determines how much water reaches the leaves. A radish plant may be able to draw on the water supply in only the upper foot of soil, whereas an alfalfa or kudzu plant may remove water from a depth of 10–15 ft. Obviously with increase in root length and branching the crop is less and less dependent upon surface soil moisture.

WATER-USE EFFICIENCY

Water-use efficiency is defined by Viets (1965) as "the quotient of dry or marketable weight of a crop produced per acre over the depth of water required in evaporation to produce the crop".

Any newly-introduced farm practice that increases yields, such as the addition of fertilizers, automatically increases the efficiency with which water is used. This is true because high yields often do not appreciably increase water removal from the soil (Weaver and Pearson, 1956; Carlson et al., 1959). This statement may seem surprising and questionable to some, for it has sometimes been stated that farm practices that increase yields also increase water demands.

In one-month studies with young sudangrass, Weaver and Pearson observed that plant population did appreciably affect evapotranspiration but nitrogen level had little effect. Since additions of nitrogen markedly increased the yields, water-use efficiency was therefore greatly increased.

An important fact to bear in mind is that if a soil is left uncropped it loses much water by evaporation. If the same soil is cropped, the water loss by evaporation decreases but loss by transpiration then becomes important. The total loss by the two processes is usually, but not always, less than that from a moist bare soil. The pounds of dry matter produced per inch of evapotranspiration can vary from near zero to a value many times larger. The data of Allison et al. (1959), although obtained from lysimeters where advection was a major factor, illustrate this point. At the lowest yields only 40 lb. of dry matter were produced per inch of water volatilized, whereas at the highest yields the value was 280 lb. The loss of water from the bare soil in this experiment was about 18 inches per year. Much smaller differences in dry matter per inch of water would be expected under field conditions, where heat from advection and light reflection would be of a much smaller magnitude. The principles involved are the same, however, under the two sets of conditions even though the extent of the differences do differ markedly.

Evapotranspiration, sometimes designated as consumptive use of water, has been shown to increase as the soil moisture level increases. Kelley (1954) assembled data on the subject, and found that at most locations the consumptive use for the wettest treatments did not exceed that for the driest by more than about 30%. He points out that the effect of soil moisture levels on the efficiency of water use by the crop was conditioned by the influence of moisture levels on plant growth. Where yields were increased by the maintenance of high soil moisture there was usually an increase in water-use efficiency; where there was no increase in crop yield there was generally a decrease in efficiency.

Organic matter in the soil commonly helps markedly in increasing water-use efficiency. This is because in one way or another it beneficially affects nearly all phases of soil and crop management. The effects of organic matter on water use are broad; an effect on one phase of crop production may affect another, and similarly, as management practices are changed the effects of organic matter may vary.

The principal contributions of organic matter to water-use efficiency are realized through: (1) increase in the percentage of rainfall that is made available for use by the crop; (2) improved physical condition of the soil that permits a greater root proliferation; (3) its content of total and available plant nutrients; and (4) its production of larger and perhaps greener plants that intercept more of the sun's rays that thereby increase the production of photosynthate.

Organic matter not only makes it possible for more of the rainfall to penetrate into the soil, but often indirectly at least aids in its more complete and efficient utilization by the crop. These effects are especially important in regions of limited rainfall, and even where the rainfall is high but not well distributed. Inadequate moisture at a critical period in the plant growth cycle, as at the time of seed formation, can markedly reduce grain yields and hence water-use efficiency. Crops, such as grasses that are grown for their total production of dry matter rather than for grain yields, are less affected by lack of moisture. This emphasizes the importance of the selection of crops that best fit the climatic conditions. Corn, with a comparatively long growing season and a need for much moisture in late summer, may fail under dryland conditions. On the same soil wheat may be grown successfully since its growth occurs chiefly when soil moisture is highest and evapotranspiration is comparatively low. Under these conditions water-use efficiency, defined in terms of grain yields, would be much higher for wheat than for corn.

The role of organic matter in making the soil a better place for root growth has already been discussed at some length in this chapter and in Chapter 16. The improved root penetration permits a better utilization of the various essential elements as well as more complete use of the water stored in the soil. This is most important under conditions of moisture stress, but improved aggregation also provides better drainage and aeration when moisture is present in excess. In either case the result is likely to be an increase in yield per unit of water utilized.

Most forms of organic matter added to soils as crop residues, animal manures, green manures, etc., contain considerable amounts of the various essential elements. These nutrients are to a large extent made available slowly and hence are very effective under conditions of adequate moisture in increasing yields with little effect on total water use. Where the carbon–nitrogen ratio of the material is too wide, yields may be decreased unless extra nitrogen is added, but this is not a serious problem in farm management. The effect of organic matter additions in increasing yields are commonly similar to that of added commercial fertilizers. In both cases water-use efficiency increases as yields increase (Weaver and Pearson, 1956). The higher levels of efficiency may not be economically feasible with fertilizers, because at these higher levels the efficiency per unit of added fertilizer decreases. This is not a problem with organic matter additions, since they are largely waste materials used at a level where yields are at a lower level.

It should be pointed out that under dryland conditions, if fertilizers stimulate growth and increase the rate of use of soil water, the available supply may be largely exhausted at a critical period of growth. If this occurs, the yields, especially of grain crops, may be lowered by the fertilizers, and water-use efficiency may be decreased. The effect under these conditions is much the same as where the rate of seeding of a crop is markedly increased. Although additions of organic matter that is well-supplied with available nutrients may sometimes increase the rate of water use, it is unlikely that this would be a factor of great importance at the rates ordinarily used.

Plants that grow on soils that are abundantly supplied with organic matter and water are likely to be larger, more vigorously growing and have a greener color during much of their growth period than where organic matter is less abundant. These large green plants not only protect the soil surface against heavy rains, but the greater amount of chlorophyll results in an increase in total photosynthesis and dry matter. Better infiltration, a more extensive root system, and more photosynthate all tend to increase water-use efficiency.

For more detailed discussions of water-use efficiency than given here, reference should be made to the article by Viets (1962) and to articles by various authors published in the book by Pierre et al. (1965).

WATER REPELLENCY

The beneficial effects of organic matter on water use, as experienced under most agricultural conditions, have been discussed above. It should be noted, however, that not all kinds of organic matter serve to increase the ease and rate of water infiltration. Certain soils are either non-wettable, or at least difficultly wettable, because of the presence of hydrophobic organic substances (De Bano, 1969; Fink, 1970). Even highly permeable sandy soils may become water-repellent if such substances are present.

Little is known about the chemical nature of these hydrophobic substances but it has been shown that they may be produced by microorganisms, particularly certain fungi (Shantz and Piemeisel, 1917; Savage et al., 1969a, b). Apparently most humic acids and polysaccharides are not responsible for water repellency in soils. Hydrophobic substances may be present in brushland soils following burning, but it is not known to what extent microorganisms are responsible for their presence. Certain brush species produce hydrophobic organic substances, and presumably a portion of these may accumulate in the upper part of the soil profile below the litter layer as a result of leaching from both the brush and decomposing parts. These substances tend to accumulate so long as the brush species are growing normally. It is the presence of these water-repellent substances that is responsible in part for severe erosion of many hilly brushland soils following burning. Rainfall that would normally soak into the soils readily, runs off instead from these soils with severe gully erosion the result.

When either surface litter or water-repellent soil was heated, De Bano et al. (1970) found that the vaporized substances condensed on the soil, and the thickness of the water-repellent layer increased as the percentage of silt and clay decreased. This effect of texture was attributed to the specific surfaces of the soils. Usually, but not always, the degree of water repellency increased as the amount of translocated organic matter increased in any given test soil.

De Bano (1969) describes certain sandy water-repellent soils commonly found in Australia. He states that "the soils here support a grass cover on 25 inches or less of rainfall annually. The pastures look patchy where well grassed areas alternate with bare areas over small distances. A close examination of these patchy areas shows that moisture penetrates only the grass areas. The intervening bare areas are dry. Even after rainstorms, these areas remain dry because the soil is extremely water repellent. The irregular wetting causes uneven germination and a patchy, less productive, pasture." The situation here seems to be in some respects similar to that encountered in peat soils that are allowed to dry out; rewetting of these may be a problem.

Fortunately, according to De Bano, water repellency appears to be a time-dependent physical property of soil; wetting resistance of a hydrophobic soil tends to decrease with time. The addition of wetting agents can also improve wetting of these soils, but no practical use is being made of this fact.

REFERENCES

Allison, F.E., Roller, E.M. and Adams, J.E., 1959. *U.S. Dep. Agric. Tech Bull.*, 1199: 1–62.

Army, T.J., Wiese, A.F. and Hanks, R.J., 1961. *Soil Sci. Soc. Am., Proc.*, 25: 410–413.

Bertrand, A.R., 1965. In: W.H. Pierre, D. Kirkham, J. Pesek and R. Shaw (Editors), *Plant Environment and Efficient Water Use.* Am. Soc. Agron., Madison, Wisc., pp. 207–235.

Bresler, E. and Kemper, W.D., 1970. *Soil Sci Soc. Am., Proc.*, 34: 3–8.
Carlson, C.W., Alessi, J. and Mickelson, R.H., 1959. *Soil Sci. Soc. Am., Proc.*, 23: 242–245.
De Bano, L.F., 1969. *Sci. Rev.*, 7: 11–18.
De Bano, L.F., Mann, L.D. and Hamilton, D.A., 1970. *Soil Sci. Soc. Am., Proc.*, 34: 130–133.
Dittmer, H.J., 1937. *Am. J. Bot.*, 24: 417–420.
Fink, D.H., 1970. *Soil Sci. Soc. Am., Proc.*, 34: 189–194.
Foy, C.D. and Brown, J.C., 1963. *Soil Sci. Soc. Am., Proc.*, 27: 403–407.
Foy, C.D. and Brown, J.C., 1964. *Soil Sci. Soc. Am., Proc.*, 28: 27–32.
Jamison, V.C., 1956. *Soil Sci.*, 81: 459–471.
Kelley, O.J., 1954. *Adv. Agron.*, 6: 67–94.
Olsen, S.R., Watanabe, F.S., Clark, F.E. and Kemper, W.D., 1964. *Soil Sci.*, 97: 13–18.
Parr, J.F. and Bertrand, A.R., 1960. *Adv. Agron.*, 12: 311–363.
Peters, D.B., 1960. *Agron. J.*, 52: 536–538.
Peters, D.B. and Russell, M .B., 1959. *Soil Sci. Soc. Am., Proc.*, 23: 170–173.
Pierre, W.H., Kirkham, D., Pesek, J. and Shaw, R., 1965. *Plant Environment and Efficient Water Use.* Am. Soc. Agron., Madison, Wisc., 295 pp.
Savage, S.M., Martin, J.P. and Letey, J., 1969a. *Soil Sci. Soc. Am., Proc.*, 33: 149–151.
Savage, S.M., Martin, J.P. and Letey, J., 1969b. *Soil Sci. Soc. Am., Proc.*, 33: 405–409.
Shantz, H.L. and Piemeisel, R.L., 1917. *J. Agric. Res.*, 11: 191–245.
Smith, F.B., Brown, P.E. and Russell, J.A. 1937. *J. Am. Soc. Agron.*, 29: 521–525.
Tackett, J.L. and Pearson, R.W., 1965. *Soil Sci.*, 99: 407–413.
Tanner, C.B. and Lemon, E.R., 1962. *Agron. J.*, 54: 207–212.
Viets Jr., F.G., 1962. *Adv. Agron.*, 14: 223–264.
Viets Jr., F.G., 1965. In: W.H. Pierre, D. Kirkham, J. Pesek and R. Shaw (Editors), *Plant Environment and Efficient Water Use.* Am. Soc. Agron., Madison, Wisc., pp. 259–274.
Weaver, H.A., and Pearson, R.W., 1956. *Soil Sci.*, 81: 443–451.
Wischmeier, W.H. and Mannering, J.V., 1965. *J. Soil Water Conserv.*, 20: 150–152.

Chapter 18

A SOURCE OF PHYTOTOXIC SUBSTANCES

INTRODUCTION

There has been so much emphasis placed on the benefits to be derived from the addition of organic matter to soils that it may be a shock to some readers to learn that sometimes certain kinds of organic matter additions, or products derived from them, are harmful to some higher plants and microorganisms. But some of these substances that are growth-inhibiting to some organisms may be growth-stimulating to others, or even to the same plants at lower concentrations. There is no sharp line of demarcation between the two opposite effects. This is in harmony with many past observations made especially with minor elements, but also with some organic substances.

The word phytotoxic carries with it the connotation of something that is harmful, undesirable, objectionable, etc. but actually strictly phytotoxic substances often play very beneficial roles. While the growth of one living organism, whether a green plant or a microorganism, is being inhibited the growth of others, because of less competition, may be favored. Whether this is desirable or undesirable in the eyes of the plant physiologist or microbiologist obviously depends upon which plant he wishes to thrive. At least, it seems that nature uses phytotoxicity as an excellent means of perfecting and maintaining an ecological balance in both macro and micro plant relationships. This should be borne in mind in a consideration of the subject.

In the discussion that follows the emphasis is placed on toxicity, even though the same substances may occasionally be stimulating under test conditions.

PAST TRENDS IN RESEARCH

Observations that indicated the possibility of the presence of phytotoxic organic substances in soils were made at least as early as the first part of the nineteenth century. This possibility was not given very serious consideration for the remainder of the century, although there were occasional references to the subject. During the past 30 to 40 years, however, as methods have improved and as all research has intensified, the subject has been given ever-increasing attention.

The literature on this subject has been thoroughly reviewed by several investigators (Evenari, 1949; Bonner, 1950; Stallings 1954; Zaumeyer, 1958; Brian, 1951, 1957a,b, 1960; Börner, 1960; Woods, 1960; Garb, 1961; McCalla and Haskins, 1964; Garrett, 1965; Jackson, 1965; Patrick and Toussoun, 1965; Rovira, 1965, and others) and hence will not be considered here in detail except for a few of the more recent publications.

This is a very active field of research at the present time that is yielding much new information on toxicity, growth stimulation, disease control, and microbial ecology. A careful reading of the review articles mentioned above tends to leave one with the impression that we have barely touched the edges of the subject of phytotoxicity. This is certainly true. The numerous sources of toxic organic substances, and the high degree of specificity with which they act on living higher plants and microorganisms, emphasize that much more work will be needed before many positive, general statements can be made without the likelihood of refutation.

There is now no longer any doubt that many toxic substances, not all of which have been chemically identified, are synthesized by higher plants and gain entrance to the soil as root exudates, leachates from leaves, fallen fruits, seeds, and as crop residues. Some of the toxic compounds are doubtless degradation split products formed by microorganisms from crop residues. In addition, many substances (antibiotics) that are commonly toxic at comparatively low concentrations are synthesized by numerous kinds of microorganisms living in the soil and gaining their growth energy from residual plant materials and root exudates.

Plant research on growth-inhibitors has been conducted largely by plant physiologists and others interested in the effect of these substances on agriculture but, as Garb (1961) points out, there has been an increasing interest in the effects of some of these substances on animal cells. Parasorbic acid, found in several plants, is a compound that has been studied rather extensively. It has been shown to have a definite differential effect on animal cells. Recently, there has been much interest in the study of inhibitors from plants in an effort to find substances that may be used in the treatment of cancer. For this purpose, narrow-spectrum rather than broad-spectrum inhibitors are required. The compound sought must inhibit tumor growth with little or no effect on other cells. According to Garb, this type of research is yielding results that are promising; not for the elimination of all cancers but rather for specific types of malignancy. This statement may be too optimistic.

ORGANIC COMPOUNDS FROM HIGHER PLANTS

Growth inhibitors are widespread throughout the plant kingdom, being produced by various families and species of green plants, as well as by many kinds of microorganisms. There is a high degree of specialization in inhibitor production; within a genus one member may form a potent inhibitor whereas other members may produce none. They are found in various parts of plants and their actions are usually specific with respect to species and part of plant affected.

Inhibitors are released from roots, chiefly, but the leaves of some plants, such as *Encelia farinosa*, a desert shrub, contain inhibitors. If in the leaves, the inhibitor may be either leached into the soil or the leaves may fall to the ground and undergo decay. The berries of some plants are also the source of growth-inhibiting substances, such as parasorbic acid found in the mountain ash (*Sorbus aucuparius*).

Bieber and Hoveland (1968) determined the phytotoxicity of several plants on seed germination of crownvetch (*Coronilla varia* L.). Water extracts of Virginia pepperweed (*Lepidium virginicum* L.), evening primrose (*Oenothera biennis* L.), crabgrass (*Digitari sanguinalis* L. Scop.) and crownvetch were most toxic, whereas tall fescue (*Festuca arundinacea* Schreb) and weeping lovegrass (*Eragrostis curvula* Nees) were least toxic.

TABLE 18.I

PLANTS REPORTED TO PRODUCE DIFFERENTIAL GROWTH-INHIBITORS OF KNOWN COMPOSITION (from GARB, 1961)

Plant sources	*Chemical constitution*	*Plants inhibited*	*Parts inhibited*	*Plants resistant*	*Comments*
Tonka bean (*Dipteryx odorata and D. opposititifolia*), sweet clover (*Melilotus*)	coumarin	carrot, onion, lily, alfalfa	roots	cress, cabbage	
Spreading pasque-flower (*Anemone pulsatilla*), buttercup (*Ranunculus*)	protoanemonin	cress, corn			
Thamnosma montana, *Angelica glabra*	byakangelicin	tomato			
Thamnosma montana	isopimpinellin	tomato			
Thamnosma montana	$C_{16}H_{15}O_5(OCH_3)$ with isobergaptene nucleus	tomato			
Guayule (*Parthenium*)	transcinnamic acid	guayule, pea		tomato	homologous
Encelia farinosa	3-acetyl-6 methoxy-benzaldehyde	tomato, pepper, corn		barley, oats, sunflower	inhibitor in leaves
Mountain ash berries (*Sorbus aucuparius*), wheat middlings, orange rind	parasorbic acid	onion, tomato	roots		
Vanilla bean	vanillin	wheat seedlings	roots		
Bergenia crassifolia	arbutin	wheat seedlings			inhibitor in leaves
Pyrus communis					
Oats (*Avena*)	scopoletin	oats			homologous
Not listed	umbelliferone	red kidney bean, cucumber seedlings	roots	peas, corn, wheat	

Aerial portions contained more extractable inhibitory substances than did the roots. Seed germination of tall fescue, ball clover, sericea (*Lespedeza cuneata* (Dumond) G. Don) and Kobe lespedeza (*Lespedeza striata* (Thumb) H. and A.) were inhibited by extracts of pepperweed. The toxic substance(s) was present in all parts of the plant, and was toxic to crownvetch at a concentration of 1:150. The extracts were also toxic to five species of fungi. When pepperweed residues were mixed with soil there was no effect on seed germination, but seedling growth was retarded. The authors were of the opinion that the toxicity of pepperweed may be of significance in its competition with other plant species.

The ease with which some organic compounds can move from or into plants was strikingly demonstrated by the experiments of Preston et al. (1954). They introduced

TABLE 18.II

PLANTS REPORTED TO PRODUCE DIFFERENTIAL GROWTH-INHIBITORS OF UNKNOWN COMPOSITION (from GARB, 1961)

Plant sources	*Plants inhibited*	*Parts inhibited*	*Plants resistant*	*Remarks*
Clover (*Trifolium*)	Kentucky bluegrass (*Poa pratensis*)		bromegrass (*Bromus inermis*) timothy (*Phleum pratense*)	
Kentucky bluegrass (*Poa pratensis*)	Canada bluegrass (*Poa compressa*)	foliage and roots		
Redtop (*Agrostis alba*)	timothy (*Phleum pratense*)	foliage and roots		
Redtop	Kentucky bluegrass (*Poa pratensis*)	foliage		
Bromegrass (*Bromus inermis*)	bromegrass seedlings			homologous
Mesquite (*Prosopis juliflora*)	tomato			
Greasewood (*Sarcobatus vermiculatus*)	tomato			
Viguiera reticulata	tomato			
Creosote bush (*Larrea tridentata*)	tomato			
Encelia frutescens	tomato			
White Bur-sage (*Franceria dumosa*)	tomato			
Wormwood (*Artemisia absinthium*)	sage (*Salvia schlarea*)			inhibitor in leaves may be absinthin
Artemisia absinthium	groundsel (*Senecio*)		*Datura*, *Stellaria*	
Peach	peach			homologous
Sorghum	other grasses			
Black walnut (*Juglans nigra*)	broomsedge (*A. virginicus*)		Kentucky bluegrass	inhibitor may be juglone

TABLE 18.II (*continued*)

Plant sources	*Plants inhibited*	*Parts inhibited*	*Plants resistant*	*Remarks*
	poverty grass (*D. spicata*)		timothy	
	blackberry (*R.* spp.)		black raspberry	
	dock		redtop	
	common cinquefoil		fleabane (*Erigeron*)	
	red pine (*P. resinosa*)		ferns	
	white pine (*P. strobus*)		asters	
	apple		goldenrods	
	potatoes		mints	
	alfalfa	leaves	violets	
	tomatoes		wild grape, clovers,	
	hydrangea		Virginia creeper	
	lilac		thistle, ironweed	
	chrysanthemum		tall oat grass,	
	asparagus		orchard grass, meadow fescue, nimblewill, velvet grass, purple top, poison ivy, corn, oats, wheat, rye, buckwheat, peach, plum, pear	
Sunflower (*Helianthus scaberrimus*)	*Helianthus scaberrimus*			homologous in spring
Rye	grapes			
Antennaria fallax	*Antennaria fallax*			homologous
Aster macrophyllus	*Aster macrophyllus*			homologous
Erigeron pulchellus	*Erigeron pulchellus*			homologous
Horse thistle	oats			
Euphorbia	flax			
Domestic ryegrass (*Lolium multiflorum*)	Kentucky bluegrass, Chewing's fescue			
Redtop	Chewing's fescue			
Butternut (*J. cinerea*)	shrubby cinquefoil (*Potentilla fruticosa*)			
Tridax procumbens	other weeds			
Zacate (*Leersia hexandra*)	rice			
Black locust (*Robinia pseudoacacia*)	white pine, barley			
White ash	white pine			
Oats, alfalfa avocado, barley, cocklebur, Sudan grass	tomato crown gall			
Evergreen creosote bush	evergreen creosote *seedlings*			homologous

alphamethoxyphenylacetic acid into the stems and leaves of bean plants and within nine hours detected it in untreated plants that were growing in the same pots as the treated ones. For further information on the extent and nature of root exudates reference should be made to the paper by Rovira (1962), discussed in Chapter 5.

An excellent summary of published information on differential growth-inhibitors derived from higher plants, published by Garb (1961), is shown here in Table 18.I and 18.II. These tables show that the production of growth-inhibiting substances by green plants is not an unusual characteristic but is indeed widespread. In considering such data it is well to bear in mind that most of the work has been done with agricultural plants or with those that affect them. As the studies are widened to include wild plants, it is highly probable that toxicity will be shown to be very widespread.

ANTIBIOTICS PRODUCED BY MICROORGANISMS

One source of phytotoxic substances in soil is the microflora that live there. Microbiologists (including the author) working in the early part of the present century with pure and mixed cultures of fungi growing on agar media had frequently noted that often the growth of one organism would inhibit the growth of others on the same agar plate. The extent of the inhibition often seemed to increase with time. In spite of this common observation it was not until Fleming's announcement in 1929 of the antibiotic effects produced by cultures of *Penicillium notatum* that it was fully realized that a chemical by-product of growth was the inhibitor. This inhibitor, penicillin, was soon shown to be effective in preventing the growth of many species of bacteria, some of which were disease producers in humans. This stimulated an intensive search on the part of medical microbiologists for other products of microbial growth that might be used in medicine. The search has continued until the present time.

Organisms involved

Thousands of species of fungi, bacteria, actinomycetes, and a few microorganisms of other groups, have been tested in pure culture under various growth conditions for antibiotic production. This work has shown that the ability to produce growth-inhibiting substances is a rather common characteristic of microorganisms, and most of those now utilized in the commercial production of antibiotics were originally isolated from soil.

In considering the mass of work that has been done on antibiotic production, allowance must be made for the fact that most of the research was for the purpose of finding antibiotics that are effective against certain pathogenic organisms and yet not appreciably toxic against humans. This limited the scope of the tests, and much of this work has little application to agriculture, especially to plant problems. Antibiotic-producing organisms that for one reason or another may be of no use in medicine may play a considerable role in the soil. Much work that is oriented toward agricultural problems remains to be done.

Since antibiotics tend to have specific effects against certain organisms, and no effects against others, it is obvious that studies must not be limited to a few test organisms if their role in ecology is to be understood.

Brian (1951) made a survey of the literature dealing with antibiotic production by fungi and found that about half of the genera and 36% of the species tested were antibiotic producers. He states further that at that time fungi were known to produce about 96 apparently distinct antibiotics, but only 57 had been well characterized. In many of the groups of fungi only a few species had been tested and then only against a very limited number of other organisms. Undoubtedly the same general conclusion could be drawn now from work with actinomycetes and bacteria if this literature were to be summarized. Brian states that the antibiotics produced by fungi show no chemical unity as a class, although some antibiotics may show similarities of chemical structure. Nearly all are lipoid-soluble, only slightly water-soluble, and mostly acidic.

The question naturally arises as to why microorganisms produce antibiotics, but there is no certain answer. These substances seem to be natural products of the growth of organisms rather than the response to some unfavorable condition in the growth medium. Antibiotics are sometimes considered as by-products of growth in the sense of being discarded non-essential waste products. There is, however, very much to indicate that antibiotics are essential products produced, perhaps, as aids in the defense of the producing organism against competing organisms. If we accept the latter viewpoint, though, we may still wonder why a given organism usually produces only a single antibiotic or, at most, only a few that are effective against only a limited number of other organisms and not against most of the competitors.

Importance of energy source

Most of the research that has been done on antibiotic production by microorganisms has been with pure cultures growing on agar plates or in solution cultures well supplied with energy sources, chiefly sugars. Under these conditions organisms that are capable of producing antibiotics commonly perform this function readily if the medium used is suitable and the other environmental conditions are optimum for the particular organism under study. The antibiotic accumulates in the agar or liquid culture medium and can be assayed by biological or chemical methods. The quantity of antibiotic produced varies widely with the type of organism and also with the species and strain used. It also varies widely with the energy source, but under favorable conditions the amount of antibiotic being produced is closely correlated with the rate of growth of the organism. As the energy source is exhausted, growth and antibiotic production also cease.

In the soil the energy source for all saprophytic organisms is chiefly crop residues present in various stages of decomposition. Sugars are present in very small amounts, and then mostly as decomposition products of crop residues or as root excretions. The kinds of organisms present are diverse and competition for the energy-yielding materials is vigorous. The species that gain dominance in this environment must be the ones that can utilize crop residues as the energy source and can grow the most rapidly, thereby literally swamping competitors and exhausting the most available constituents in the residues. Antibiotic-producing organisms are present along with other saprophytes but obviously the opportunities for producing antibiotics are limited and differ markedly from the conditions in pure cultures. The result in this case would depend primarily on how well the added organism could utilize the plant residues.

Studies conducted with pure cultures of fungi and actinomycetes added to sterile amended soil singly and in various combinations have shown that antagonism between organisms is common. This is true for those that do not produce antibiotics as well as for those that do, but the latter may have some advantage over the former. As Brian (1957b) states "one has to envisage a complex web of antagonisms existing in mixed cultures, the potential antagonistic properties of one species being influenced by others." Under such conditions antibiotic production by any one of the antagonists is likely to be markedly curtailed.

In normal soils it has been shown by a few workers that small amounts of antibiotics are sometimes formed following the addition of fresh plant materials. Many other workers have been unable to demonstrate this and have sometimes been surprised at the negative results. It seems to the writer that there should be little reason for surprise in this case considering the many reasons for expecting negative results. There is a large and unknown number of both antibiotic-producing and nonantibiotic-producing organisms present in most any soil that are competing for the energy supply, each fraction of which is probably available to a large number of types of organisms, including fauna. We must, therefore, logically assume that several kinds of antibiotics are being produced in driblets, and not just one. Which one of the many should the experimenter test for? It is certainly impractical, or even impossible, to test for a hundred or more antibiotics, and the ones not assayed may be the chief ones present. Furthermore, the methods of assay are usually not sufficiently sensitive for the assays that he chooses to make, bearing in mind that in most cases only mere traces would be expected.

The above discussion has been concerned with conditions where the available energy supply was abundant. In soils where no plant residues or other energy sources have been added for a year or longer, and no crop is present, the likelihood of demonstrating the formation of antibiotics should indeed be slight. In such soils the available energy supply has been reduced to such a low level that both growth and antibiotic production are limited. Available energy supply is of first importance in antibiotic production just as in most other microbial processes.

In considering the energy sources for antibiotic production the emphasis here has been placed on crop residues. It is barely possible that under some conditions in cropped soils the main energy source used in antibiotic production is the root exudates. Plants exude sugars and other simple compounds that are especially suitable for most antibiotic-producing organisms. It is also well established that many antibiotic-producing microorganisms are found in the rhizosphere and in numbers far exceeding that at a few millimeters distance. We are somewhat uncertain as to the amount of energy materials released from the roots of various plants but the number of organisms present in any given rhizosphere is a fair estimate of the amount of food being released; microorganisms use nearly all of the food released and as fast as it is exuded. Any antibiotic produced in the rhizosphere would be in a position to produce maximum effects, whether good or bad, on plant growth since it would be in immediate contact with the roots. Neither biological decomposition, nor adsorption by clays, would likely be a major factor in decreasing the activity of the antibiotics on the plant (see following discussion).

Fate in soil

Another reason why antibiotics are not detected in soils in appreciable amounts, if at all, is that most of them are highly labile and are rapidly degraded. In some cases the breakdown is attributable to chemical instability caused by pH, but more often it is the result of biological attack. Since most naturally occurring compounds are subject to microbial attack it is likely that all antibiotics are susceptible.

Adsorption of antibiotics by clay minerals also plays a very important role in reducing their activity and in decreasing the chance of their detection (Pinck et al., 1961a,b). The basic antibiotics, such as streptomycin, aureomycin, neomycin, terramycin, actinomycin and some bacterial polypeptide antibiotics, are rather strongly held by clays. Neutral and acidic antibiotics are either not adsorbed or only weakly held. The present limited information indicates that antibiotics are not biologically active so long as they remain strongly held by clays. When removed by suitable extractants they regain their original activity.

Phytotoxicity

Most antibiotics that have been tested show some degree of toxicity to higher plants, but it is also true that several of them have been shown to stimulate plant growth. The effect produced varies widely with the antibiotic used and its concentration, the plant part treated, and the extent to which it is absorbed and translocated. In general, movement through plants is rather difficult, especially for the basic antibiotics; the acidic and neutral ones are more readily translocated.

Antibiotics have been shown to affect photosynthesis, organic acid synthesis, chromosomes, certain enzymatic processes, pigmentation, plastid formation, germination, root growth, and in fact most phases of growth. Just as the specificity of antibiotics against bacteria and fungi varies markedly, so do the effects against higher plants. Likewise, an antibiotic that is especially toxic to root elongation may, for example, have little effect on seed germination.

The toxicity of a number of antibiotics to germination and seedling root growth of wheat, clover and mustard was reported by Wright (1951). Coumarin and 3-indolylacetic acid were also included in the tests. The percentage germination of wheat at the concentration used (1–25 μ g/ml) was not markedly affected by any of the compounds tested but root growth was reduced. In the case of mustard and clover, severe inhibition of both germination and root growth occurred with some antibiotics. Most of them were more toxic than coumarin but less toxic than indolylacetic acid. Alternaric acid, glutinosin, mycophenolic acid and gliotoxin were the most toxic antibiotics; griseofulvin, penicillin and streptomycin were least toxic. Table 18.III shows the results obtained by Wright with red clover seeds and seedlings at two pH values.

TABLE 18.III

TOXICITY OF VARIOUS ANTIBIOTICS, 3-INDOLYLACETIC ACID, AND COUMARIN TO RED CLOVER SEEDS (from WRIGHT, 1951)

Compound		*% germination*				*Root growth as % of control*		
		25	*5*	*1 (p.p.m.)*	*0*	*25*	*5*	*1 (p.p.m.)*
3-Indolylacetic acid	*a**	1	3	33	70	< 1	< 1	2
	b	2	15	60	77	< 1	< 1	8
Coumarin	*a*	100	97	97	98	41	66	94
	b	100	100	98	97	68	82	79
Penicillin	*a*	98	100	98	100	85	102	98
	b	100	98	100	98	109	105	95
Streptomycin	*a*	100	100	98	100	99	95	105
	b	97	95	100	98	104	105	117
Patulin	*a*	97	95	98	97	9	50	85
	b	95	100	97	100	7	50	88
Citrinin	*a*	22	68	73	70	< 1	62	73
	b	13	53	72	70	3	39	80
Griseofulvin	*a*	78	95	99	99	23	72	85
	b	83	99	97	97	21	63	87
Griseofulvic acid	*a*	43	75	90	85	13	47	102
	b	53	72	77	90	16	51	93
Mycophenolic acid	*a*	7	35	70	78	1	23	74
	b	12	12	68	78	3	9	72
Glutinosin	*a*	3	55	73	83	–	13	52
	b	5	47	70	85	–	8	35
Gliotoxin	*a*	89	97	100	99	4	25	88
	b	80	99	99	99	3	21	94
Viridin	*a*	85	97	100	97	26	66	94
	b	95	100	97	99	41	88	100
Gladiolic acid	*a*	100	100	100	98	20	58	84
	b	100	100	100	100	34	68	80
Albidin (red pigment)	*a*	87	97	98	100	5	37	87
	b	80	94	97	98	8	61	96
Alternaric acid	*a*	77	98	100	98	17	89	105
	b	67	97	98	100	15	73	86

**a* = pH 4.0; *b* = pH 6.0.

Goodman (1959) discusses the phytotoxicity of streptomycin, cycloheximide, griseofulvin, polymyxin and tetracyclines. These are antibiotics that have been most used, or considered for use, in plant disease control. Other antibiotics that he mentions which have been observed to be phytotoxic are alternaric acid, glutinosin, mycophenolic acid and gliotoxin.

The effect of some 38 antibiotics on plants was reviewed by Brian (1957a). He states that four antibiotics consistently inhibit seed germination or root growth at concentrations of 5 μ g/ml or less. These are actidione, azaserine, alternaric acid and polymyxin, all of which show considerable specificity in their action. Actidione reduces root growth of peas at 1 μ g/ml and is also toxic to foliage. This antibiotic produces roots of reduced size but the epicotyls are much longer and stouter than in untreated plants. Azaserine inhibits root growth of several species in the range of 1–10 μ g/ml but even large doses have little effect on shoot growth. Alternaric acid, like actidione, is very inhibitory to root growth and is also toxic to shoots. Polymyxin has been shown to inhibit root growth but in the presence of Ca^{2+} the effect of the antibiotic is reversed. Brian emphasizes that there is such a mass of diverse observations in the antibiotic literature that a critical review is not yet possible.

Norman (1959) tested twenty newer antibiotics to determine their activity in repressing elongation of roots of cucumber and growth of barley roots. At concentrations of 10 μ g/ml repression of root elongation and root growth was found in most tests. These results show that certain antibiotics are strong inhibitors of root growth and, if produced in appreciable amounts in the rhizosphere, can be expected to have a marked effect in reducing the total growth of the crop.

In another paper, Norman (1960) listed 14 common antibiotics that, in general, repress root growth or root development at levels mostly well below 10 μ g/ml; 7 others were distinctly less active. He states that, for injury to occur, entry of toxic substances into roots in the conventional sense may not be necessary. Surface adsorption on the root epidermis or in free space, as defined by plant physiologists, may also result in decreased root growth.

The mechanisms by which antibiotics exert their phytotoxic effects are for the most part unknown. There are doubtless many mechanisms. However, Brian (1957a) states that in the case of polymyxin this antibiotic apparently disorganizes the cell membranes of surface root cells, possibly as a result of its marked surface activity, and the cell contents leak out. Whether other polypeptide antibiotics produce root injuries by the same mechanism is not known.

Brian also calls attention to the fact that certain parasitic microorganisms within plant tissues can produce antibiotics that are toxic to their hosts. Among these are lycomarasmin, fusarinic acid, alternaric acid and patulin. There appears to be considerable doubt as to the connection between these antibiotics and the development of disease symptoms in the host plants. Definite conclusions must await further research.

SOME INTERESTING OBSERVATIONS

In recent years there has been a surprisingly large number of reports of instances where the turning under of certain crop residues injured the germination and growth of crops that followed, or where crop growth was markedly depressed following the growth of certain other crops. In other cases where certain tree crops have been grown for a number of years, and the old trees have been removed, young replants may fail to grow vigorously. In many, or perhaps most, of these cases research has shown that many factors, such as soil fertility, fungus diseases, nematodes, bacteria, aeration, etc. are likely to be involved, but in addition there is often strong evidence for injury by phytotoxic substances. Injury produced by such substances is seldom the only factor involved but an important one, especially if superimposed on other factors that are limiting normal growth.

The various review articles mentioned above list many instances where phytotoxicity appears to be involved, although often definite proof that phytotoxic compounds played the major role has not been obtained. Space does not permit detailed discussion of all of these observations, but reference will be made to several observations that are of unique or practical interest. Where documentation is omitted the reference will usually be found in one or another of the review articles. Some of the plants mentioned are listed in Table 18.I and 18.II.

Guayule plants were observed to inhibit the growth of one another when planted in close proximity. When nutrient solutions were leached through sand cultures of one-year old guayule plants and supplied to younger plants growth of the latter was inhibited. Control plants that received none of the leachate grew rapidly. The leachate had no effect on the growth of tomatoes. The toxic compound was determined to be cinnamic acid, a normal constituent of the guayule plant and not a product of microbial decomposition of dead roots. When added to sterile soil it is stable but it disappears rapidly in nonsterile soils. This indicates that under normal growing conditions, where marked toxicity is encountered, the compound is being excreted from the guayule roots constantly.

Another interesting case of phytotoxicity, mentioned by Bonner (1950), is that of *Encelia farinosa*, a desert shrub. This plant, unlike most desert shrubs, does not harbor a growth of annuals under its branches. Investigations gave no indication of excretion of toxins from the roots but when leaves were added to soil, pepper, tomato and corn plants were severly injured or killed; barley, oats and sunflower were little affected. The toxic substance was shown to have the structure 3-acetyl-6-methoxybenzaldehyde. When leaves of the plant fall on the ground they retain their toxicity for a year or more even though much of the phytotoxin is leached into the soil.

Another plant that produces a toxin in its leaves is the shrub, *Artemesia absinthium.* The toxin may be leached from the leaves by rainfall and severely stunt other species growing nearby.

Bevege (1968) watered young hoop-pine (*Araucaria cunninghamii* Ait.) seedlings for 10 months with leachates from sand in which either advanced hoop-pine, slash pine (*P.*

elliottii Engl.) or crows ash (*Flindersia australis* R. Br.) were growing, and observed a significant reduction in dry-matter production and some stunting and mortality. The leaching solution consisted of a complete nutrient medium. Two inhibitory systems in the leachates are postulated, "one inhibiting phosphorus uptake, the other causing symptoms similar to nitrogen and potassium deficiency but possibly acting through some other metabolic pathway."

The black walnut tree has often been observed to inhibit the growth of numerous species of plants (see Table 18.II). The area of inhibition usually corresponds closely with the spread of the root system. Juglone (5-hydroxynaphthoquinone), which is present in both the roots and aerial parts of the plant is thought to be the toxic factor.

When young peach trees are planted in an old peach orchard they often grow poorly. As McCalla and Haskins (1964) state, the factors involved probably include soil toxins, nematodes, fungi, bacteria and soil fertility. Amygdalin, which is not itself toxic, is present in peach roots and on decomposition can yield toxic substances that in part account for stunting of the young peach trees.

The replant problem is also a serious one in many citrus groves. As in the case of peach trees, it seems that a number of factors, especially microbiological ones, are involved but there is also evidence for a toxic substance possibly produced by microorganisms growing on old citrus roots.

Börner (1960) states that soil sickness in fruit culture is a problem of economic importance in Germany. This is a replant problem that involves micro-element depletion and nematodes, but also root residues. As little as 1 g of air-dry root bark of an old apple tree per half liter of nutrient solution reduced root and stem growth of apple seedlings up to 50% within 30 days. Phlorizin, a natural constituent of apple root bark, and its breakdown products, are at least partially responsible for this apple soil sickness.

Phytotoxic substances have been shown to be present in a number of tree products. Allison (1965), for example, tested the woods and barks of 28 species on garden peas growing in soil containing the wood products together with adequate supplemental nitrogen and observed some toxicity in six of these species. The bark of California incense cedar was slightly toxic to growth, and the wood was very toxic to both germination and growth. White pine bark was very injurious to pea seedlings at the 1- and 2% rates. Red cedar wood and bark, yellow poplar bark, and the woods of Ponderosa pine and loblolly pine, slightly injured growth. In all instances the toxicity decreased somewhat during the six-week period following addition to soil but was still in evidence on a second planting of peas.

Sometimes in nature plants are observed to form single stands that cannot be attributed to the soil or environmental conditions. Garb (1961) suggests that this can be explained on the basis that some plants may secrete a broad-spectrum inhibitor. He hypothesized that when the density of the plants passes a critical point, the inhibitor will prevent all other kinds of plants from growing there, and a single stand is the result. This is an interesting possibility, which, if proven true, would certainly emphasize the importance of plant-produced phytotoxins in plant ecology. At least, numerous examples of plants that inhibit the growth of other plants are known even if the formation of single stands may be very unusual. As Garb states, the complexion of plant communities is often dependent upon toxin production by some plants and of toxin tolerance by others.

Growth inhibition of plants where crop residues are undergoing decay has been observed. For example, McCalla and Army (1961) observed that where wheat straw was left on the soil surface in a stubble mulch system of farming the growth of corn was sometimes retarded. The effect was observed on the very young plants which never recovered during the entire season.

In a follow-up of the observations of McCalla and Army studies were made by Guenzi and McCalla (1962) of the effect of extracts of several crop residues on germination and seedling development of corn, wheat and sorghum. All of the residues contained water-soluble substances that were toxic to these three plants. In other studies Guenzi et al. (1967) found that the order of increasing toxicity to wheat seedlings of the water-soluble extracts was wheat, oat, corn and sorghum residues. After two months' exposure under field conditions the toxicity of wheat and oat residues had disappeared; the corresponding time was 5 to 7 months for corn and sorghum residues. Alfalfa forage also contains water-soluble substances that were shown by Guenzi et al. (1964) to inhibit shoot and root growth of corn seedlings.

Guenzi and McCalla (1966) extracted soils with various extractants, and by paper chromatography identified several phenolic acids. The concentrations were probably too low to produce appreciable effects on plant growth if we assume even distribution throughout the soil. Much higher concentrations of the phytotoxins would be expected in the immediate vicinity of decaying crop residues.

Norstadt and McCalla (1968) observed the formation of patulin, a potent phytotoxic substance, in soil amended with wheat straw. This was apparently produced by *Penicillium urtricae* Bainier, since the presence of the residues favored growth of the fungus, and phytotoxicity increased with growth.

Water extracts of wheat straw that had been rotted for up to 6 weeks were shown by Kimber (1967) to inhibit the growth of wheat and oat seedlings maintained under aseptic conditions. Roots were much more affected than shoots by the inhibitors. Under field conditions, weathering reduced the inhibitory effect. Microorganisms were apparently responsible for both the formation and decomposition of the plant toxins.

In experiments conducted by Bowen and Rovira (1961) with four kinds of plants grown in a complete nutrient solution (sand and agar cultures), it was observed that the presence of microorganisms added as a soil suspension reduced primary root growth in all plants, and total root growth in most plants. Root-stunting microorganisms were present in all four soils used but the extent of stunting varied with the soil. The inhibition of root growth was observed 5 days after planting and inoculation of subterranean clover, and after 9 days with tomato. The production and growth of root hairs by subterranean clover were markedly reduced in sand cultures and the effect was apparent after 3 days. Only slight root-hair reduction was observed with tomato and phalaris. Since these root-inhibiting effects followed the addition of suspensions of unamended soils, very low in available energy, it seems probable that the effects would be in harmony with the field observations reported by McCalla and Army, discussed above.

Germination inhibition and retarded growth of seedlings has frequently been observed following the turning under of green manures or crop residues. Often fungal diseases are responsible for such effects but there are also a number of substances, including antibiotics, that are known to be at least partially responsible for such effects. Even free, unionized ammonia, produced from plant products having narrow carbon–nitrogen ratios, can produce injury (Megie et al., 1967). Nitrite is also toxic at low concentrations, and under partially anaerobic conditions hydrogen sulfide may be produced.

Megie et al. reported that 1:50 plant–water extracts of fresh plant residues had little effect on the germination of cotton, but with onset of microbial decomposition, extracts of all materials were highly toxic. The authors state that the presence of a toxic constituent, possibly saponin, was indicated. Certainly antibiotics were also present although probably not in toxic concentrations.

Substances that markedly inhibited the germination, respiration and growth of tobacco were obtained by Patrick and Koch (1958) after residues from timothy, corn, rye and tobacco plants were allowed to decompose. The respiration of tobacco seedlings was reduced by 50–90% by residues of any of the crops that had been allowed to decompose for 15 to 25 days in the presence of high soil moisture and at pH values below 5.5. Toxicities of the residues decreased in the order given above. Darkening and necrosis of root cells accompanied the respiration inhibition. Timothy and barley were also injured. Although the toxic substances were not identified they were shown to be water soluble, heat stable, and also stable in acids. The authors were of the opinion that the toxins may act in the field as the primary cause of some root rots, and in predisposing plants to attack by organisms not normally regarded as pathogenic.

Extracts of certain soils, especially of muck and bog soils, and sometimes of forest soils (Persidsky and Wilde, 1954) have frequently been shown to be toxic. Toxicity in such cases may be either of chemical or microbial origin depending both upon the soil itself and on the conditions under which it existed in nature. In fact, some of the first work on toxicity was done by Schreiner and Shorey in 1909 when they attempted to explain the low productivity of certain soils. They isolated dehydroxystearic acid and vanillin and showed them to be toxic to plants in aqueous solution. Undoubtedly they overemphasized the practical importance of these compounds, but they at least demonstrated at an early date that toxic organic materials do exist in soils.

AGRICULTURAL SIGNIFICANCE OF PHYTOTOXINS

Much of the research in the field of plant growth inhibitors is comparatively recent and incomplete, and hence a fair evaluation of the role of phytotoxins in crop production can scarcely be made. No longer do we doubt, however, that a wide variety of such substances exists in many kinds of plants and of course in their residues that remain in the soil or are returned to it. Additional toxic substances may be produced by microorganisms both as degradation products of plants and as synthetic products of the organisms. Fortunately, most of these phytotoxins are either decomposed or inactivated within a few days or weeks in the soil but there are exceptions that can at times markedly depress the yields of certain crops.. There is usually marked specificity on the part of the sources of phytotoxicity, and also on the crops that they affect. It is largely this specificity that accounts for some unusual crop rotation effects where a certain crop may depress yields of a crop that follows but have no effect on another in a different rotation. Some weeds may also be very harmful to crops for reasons that are not obvious, but they may also be beneficial (Brown and McMurtrey Jr., 1934; Lunn et al., 1939).

Börner (1960) reviewed the information on the effect of one plant on another (allelopathy) and concluded that "the combined effects of soil microorganisms and the physical forces in the environment often serve to distract attention from the effect of soil toxins, but there is enough evidence to be certain that some soils are made poisonous to plants by organic compounds from preceding crops." Garb (1961), likewise, concluded that "differential plant growth-inhibitors appear to play a substantial role in many botanical relationships. They may prove to be important factors in agriculture and ecology." Russell (1961) gives a good general discussion of the effect of growing plants on the soil and on each other. Research data obtained since the publication of these papers have further strengthened the statements of these two authors.

An excellent discussion of the significance of phytotoxins formed from crop residues, allowed to decompose under field conditions, is given by Patrick and Toussoun (1965). Their conclusions are based in large part on their own experimental results (Patrick and Koch, 1958; Patrick et al., 1963). They emphasize that phytotoxins form readily early in the decomposition of plant residues, especially when the oxygen supply is deficient in the soil as a whole, or in localized pockets. Soil conditions that favor phytotoxin formation are believed to be more common than is generally realized. These harmful substances formed in plant residues do not diffuse far into the soil mass; they are readily inactivated or adsorbed near the soil-residue interface. Since cover crops and plant residues are commonly added to soil in clumps with no uniform mixing, any phytotoxins formed would therefore be irregularly distributed in the soil. Any plant root might therefore be subject to high toxins at one place and none a few inches away. Field observations by Patrick and co-workers showed that discolored or sunken lesions on roots did commonly occur where a root was in close proximity to fragments of decomposing plant debris. They observed various effects on the roots, including inhibitions of root-hair formation and marked reduction in respiration. Most of the injurious effects were irreversible, that is, young plants so injured did not recover. The weakened plants would doubtless be less able to resist invasion by plant pathogens. These authors emphasize that the beneficial effects of plant residues far outweigh their detrimental effects, but the latter should not be overlooked.

Phytotoxins synthesized in the rhizosphere by microorganisms may play a greater role in plant growth than those derived from the breakdown of crop residues. This is chiefly because the rhizosphere flora feeds on a continuous supply of exuded food that is especially suitable for antibiotic-producing microorganisms. The antibiotics produced, which are mostly toxic at comparatively low concentration, are in direct contact with the root surface immediately after release. Even though the concentration of antibiotic may be low at any given time the total season uptake by the higher plant might be enough for considerable growth effects, whether stimulating or inhibitory.

Microbial ecology is also markedly affected by phytotoxins, especially by the synthetic products of microorganisms. This is obvious since an organism may produce a substance that is toxic to some organisms but not to all. Because of this selectivity it is theoretically possible for a slow-growing antibiotic-producer to actually suppress fast-growers that are susceptible to the antibiotic that it is producing. This effect on ecology may be of considerable economic importance in disease control, as is emphasized in the chapter that follows.

REFERENCES

Allison, F.E., 1965. *U.S. Dep. Agric. Tech. Bull.*, 1332: 1–58.

Bevege, D.I., 1968. *Plant Soil*, 29: 263–273.

Bieber, G.L. and Hoveland, C.S., 1968. *Agron. J.*, 60: 185–188.

Bonner, J., 1950. *Bot. Rev.*, 16: 51–65.

Börner, H., 1960. *Bot. Rev.*, 26: 393–424.

Bowen, G.D. and Rovira, A.D., 1961. *Plant Soil*, 15: 166–188.

Brian, P.W., 1951. *Bot. Rev.*, 17: 357–430.

Brian, P.W., 1957a. *Ann. Rev. Plant Physiol.*, 8: 413–426.

Brian, P.W., 1957b. In: *Microbial Ecology*. Cambridge University Press, London, pp.168–188.

Brian, P.W., 1960. In: D. Parkinson and J.S. Waid (Editors), *The Ecology of Soil Fungi.* Liverpool University Press, Liverpool, pp. 115–129.

Brown, D.E. and McMurtrey Jr., J.E., 1934 . *Md. Agric. Exper. Stn. Bull.*,363: 401–410.

Evenari, M., 1949. *Bot. Rev.*, 15: 153–194.

Garb, S., 1961. *Bot. Rev.*, 27: 422–443.

Garrett, S.D., 1965. In: K.F. Baker and W.C. Snyder (Editors), *Ecology of Soil-borne Plant Pathogens.* Univ. Calif. Press, Berkeley, Calif., pp.4–17.

Goodman, R.N., 1959. In: H.S. Goldberg (Editor), *Antibiotics – Their Chemistry and Non-Medical Uses.* Van Nostrand, Princeton, N.J., pp. 322–448.

Guenzi, W.D., Kehr, W.R. and McCalla, T.M., 1964. *Agron. J.*,56: 499–500.

Guenzi, W.D., McCalla, T.M. and Norstadt, F.A., 1967. *Agron. J.*, 59: 163–165.

Guenzi, W.D. and McCalla, T.M., 1962. *Soil Sci. Soc. Am. Proc.*, 26: 456–458.

Guenzi, W.D. and McCalla, T.M., 1966. *Soil Sci. Soc. Am. Proc.*, 30: 214–216.

Jackson, R.M., 1965. In: K.F. Baker and W.C. Snyder (Editors), *Ecology of Soil-borne Plant Pathogens.* Univ. Calif. Press, Berkeley, Calif., pp. 363–373.

Kimber, R.W.L., 1967. *Aust. J. Agric Res.*, 18: 361–374.

Lunn, W.M., Brown, D.E., McMurtrey Jr., J.E. and Garner, W.W., 1939. *J. Agric Res.*, 59: 829–845.

McCalla, T.M. and Army, T.J., 1961. *Adv. Agron.*, 13: 125–196.

McCalla, T.M. and Haskins, F.A., 1964. *Bacteriol. Rev.*, 28: 181–207.

Megie, C.A., Pearson, R.W. and Hiltbold, A.E., 1967. *Agron. J.*, 59: 197–199.

Norman, A.G., 1959. *Soil Sci. Soc. Am., Proc.*, 23: 368–370.

Norman, A.G., 1960. *Int. Congr. Soil Sci., 7th, Madison, Wisc. Comm. III*, 2: 531–536.

Norstadt, F.A. and McCalla, T.M., 1968. *Soil Sci. Soc. Am., Proc.*, 32: 241–245.

Patrick, Z.A., Toussoun, T.A. and Snyder, W.C., 1963. *Phytopathology*, 53: 152–161.

Patrick, Z.A. and Koch, L.W., 1958. *Can J. Bot.*, 36: 621–647.

Patrick, Z.A. and Toussoun, T.A., 1965. In: K.F. Baker and W.C. Snyder (Editors), *Ecology of Soil-borne Plant Pathogens.* Univ. Calif. Press., Berkeley, Calif., pp. 440–459.

Persidsky, D.J. and Wilde, S.A., 1954. *Plant Physiol.*, 29: 484–486.
Pinck, L.A., Holton, W.F. and Allison, F.E., 1961a. *Soil Sci.*, 91: 22–28.
Pinck, L.A., Soulides, D.A. and Allison, F.E., 1961b. *Soil Sci.*, 91: 94–99.
Preston, W.H., Mitchell, J.W. and Reeve, W., 1954. *Science*, 119: 438.
Rovira, A.D., 1962. *Soils Fert.*, 25: 167–172.
Rovira, A.D., 1965. In: K.F. Baker and W.C. Snyder (Editors), *Ecology of Soil-borne Plant Pathogens.* Univ. Calif. Press, Berkeley, Calif., pp.170–186.
Russell, E.W., 1961. *Soil Conditions and Plant Growth.* Longmans Green, London, 9th ed, 688 pp.
Stallings, J.H., 1954. *Bacteriol. Rev.*, 18: 131–146.
Woods, F.W., 1960. *Bot. Rev.*, 26: 546–569.
Wright, J.M., 1951. *Ann. Bot.*, 15: 493–499.
Zaumeyer, W.J., 1958. *Ann. Rev. Microbiol.*, 12: 415–440.

Chapter 19

A FACTOR IN PLANT DISEASE CONTROL

INTRODUCTION

The amount and type of organic matter in soils plays a role in the extent to which a crop is affected by certain plant diseases. In some cases, organic matter may increase the incidence and severity of a disease but under proper management beneficial effects can usually be realized. This applies particularly to diseases produced by fungi but also to those caused by bacteria, actinomycetes and possibly viruses and nematodes.

The soil is the natural home or resting place of essentially all plant disease-producing microorganisms. Some of them live here from year to year in a vegetative stage, whereas others are commonly found as spores, sclerotia, or other resting structures. The soil is even a main source of organisms that attack only the above-ground portions of plants. The causative organisms in such diseases may either harbor over from year to year in the spore stage in the soil or in the diseased tissues that fall to the soil and which may or may not be incorporated with it.

In the early years of this century plant pathologists were inclined to limit their researches to the obtaining of all possible information about the causative agent, mechanisms of action, and control of a given disease, considered as caused by a single pathogen. In more recent years they have come to realize that this is much too narrow a viewpoint. In more cases than not, many kinds of organisms play a role in determining the severity of a disease. This is especially true of diseases that affect plant roots; in fact, the damage done may not be the result of the growth of any one organism but rather the combined effect of many kinds of organisms, some of which are not even commonly classified as pathogenic. The realization of these facts has led to a wedding of the plant pathologists and the soil microbiologists. The result has been a gradual gaining of knowledge not only of the action of various disease organisms but of the interaction of all kinds of organisms in the soil. This is the science of ecology, in which organic matter plays such a dominant and controlling role. One aspect of this that is receiving much attention now relates to the biological control of soil-borne plant pathogens. Our knowledge of the subject, which is still rather meager, is thoroughly reviewed from various angles by several investigators who participated in a symposium on the subject at the University of California (Baker and Snyder, 1965). Some aspects of the subject that relate to soil organic matter are discussed below.

RESEARCH TRENDS IN ROOT-DISEASE INVESTIGATIONS

A brief discussion of research trends in the field of plant disease control will be helpful in the consideration of recent developments in nonchemical methods of disease control.

Most of the early work in plant pathology was concerned with air-borne diseases of the above-ground portions of plants, caused by fungi. Koch in 1882 (see Garrett, 1960) proposed four postulates for establishing the cause of a parasitic disease, namely: (1) constant association of the organism with the disease; (2) isolation of the organism in pure culture; (3) reproduction of the disease by inoculation with the pure culture of the organism; and (4) re-inoculation of the organism from the inoculated diseased host, and identification of it with the original inoculant.

Although these postulates, especially the first one, can be applied readily to air-borne diseases, where the causative organism is usually macroscopically obvious, the situation is very different in root diseases where many organisms are involved. If spores are observed either on the roots or above ground, there is usually no certainty that these are produced by the parasite that is being sought. Often the observed spores are the fruits of nonpathogens. When attempts were made in the past to prove that an isolated organism was the disease-producer, failure was often encountered even if the pathogen had been isolated. A number of factors were often involved but we now know that one of the main ones was inadequate inoculum potential, discussed below in another section.

The causative agents for most of the common diseases produced by fungi were, regardless of the difficulties, finally isolated and identified. Attention was then directed toward their control. Considerable research was done on the effect of temperature and moisture content, often using sterilized or partially sterilized soils kept in the greenhouse. These results were not very rewarding and, in fact, often gave misleading results so far as field application was concerned, because consideration was not being given to the mass of nonparasitic organisms that inhabit soils and compete with the pathogens.

It was during the period of about 1920 to 1930 that plant pathologists began to realize that in dealing with soil-borne diseases soil microbiology cannot be ignored. This fact was brought home to them by the discovery that under some conditions diseases, such as potato scab and take-all disease of wheat, can be controlled or greatly curtailed either by the turning under of green manures or by the addition of certain rapidly growing saprophytes or mixtures of antagonistic fungi or bacteria. It was shortly after this that the era of antibiotics was ushered in and thus a new explanation for antagonism was found that in many respects outweighed the older fact of competition for food, air, and space. There was now reason to believe that the toxic by-products of microorganisms might be largely antibiotics.

Since these demonstrations of the importance of antagonism in plant disease control much work has been done with some success but with more failures (Wood and Tveit, 1955). Perhaps the main fact that has been driven home is that the soil is a very complicated environment where so many biological, physical, and chemical factors are involved that even exact experimentation is difficult. If one attempts to isolate the factor that he wishes to study, as by sterilization and re-inoculation of a soil, he usually finds that the results obtained are of little value under field conditions. If he works with natural soils, as found in the field, then the results are influenced by such a multitude of organisms and factors that it is almost impossible to interpret or reproduce the results. Some progress, even if limited, is being made, however, and interest in the biological control of soil-borne diseases has been increasing markedly.

In the latter part of the nineteenth century a few claims were made to the effect that bacteria are responsible for many plant diseases but most pathologists were skeptical about accepting these claims. The leader in this new field was Erwin F. Smith of the U.S. Department of Agriculture who proved the bacterial nature of five troublesome plant diseases. It is now established that over 200 species and varieties of bacteria cause such diseases (Burkholder, 1948). Five genera contain the majority of plant pathogens. These are *Pseudomonas, Xanthomonas, Agrobacterium, Corynebacterium* and *Erwinia*. Most vegetable, fruit, and field crops, and to a lesser degree ornamental crops, are affected by at least one bacterial disease.

The control of bacterial diseases of plants has been less satisfactory than that of fungous diseases. Spray applications are seldom effective since many of these diseases are systemic. The use of disease-free seed, seed stock, or disease-resistant varieties has proven most effective.

The early work on virus diseases was with those caused by aerial vectors, mostly insects. This work showed that the host range of the viruses is often wide and there are many opportunities for infection by insects (Bawden, 1957). Plants raised from seed were usually found to be free of air-borne viruses initially but often became infected soon after germination. Although it had long been known that bacteriophages occurred in soil, it was not until about 1958 that it was established that soil organisms can harbor other kinds of viruses that may infect plants. This discovery came so recently that our knowledge of these diseases, and the mode of transmission, is still rather meager (Cadman, 1965). This has been and still is an active field of research.

The rate of progress made in nematology during the early years of the present century was slow largely because of a great scarcity of scientists trained in this field. This scarcity was in turn largely the result of the lack of emphasis put on the subject in both the universities and the experiment stations during the early years. The importance of these soil organisms was not appreciated. Nematodes were almost completely neglected by soil microbiologists because their interest was from the very beginning of the science in the soil flora and not in the fauna. Likewise, there was little emphasis placed on nematodes by those concerned with animal metabolism, except for the forms that produce diseases in animals. Eventually an occasional department of nematology was set up where more and more attention was given to soil forms, both pathogenic and nonpathogenic. It might have been better if the study of nematodes had been conducted in the older branch of soil microbiology rather than have it regimented in a separate section.

During the past 30 years this neglect of a very important phase of soil biology has been remedied and nematology is now an active research field. Nematodes are now known to be very numerous in soils and to play a very important part in their interrelations with a large majority of the other soil inhabitants, as well as with the higher plants that live there. Unfortunately, a few species are very injurious to plants, and some act as vectors of virus diseases, but others are not responsible for plant diseases and very likely are beneficial. These organisms play important and varied roles in microbial ecology in the soil.

One of the most intriguing and least understood phases of biological control of plant disease-producing organisms involves the nematode-trapping fungi. The existence of such organisms has been known since the latter part of the nineteenth century but it was the publication by Drechsler (1937) that initiated active research in this field. Even at present our knowledge of the practical importance of these organisms is almost nil.

MICROORGANISMS PRIMARILY INVOLVED AND THEIR RELATION TO ORGANIC MATTER

Plants are affected by a wide variety of diseases that are caused by fungi, bacteria, actinomycetes, viruses and nematodes. In the case of soil-borne pathogens the energy source for these organisms must come primarily either from their hosts, from organic residues in the soil, or at times from both living and dead tissues. It is this requirement for an energy source that makes soil organic matter such an important factor in determining the severity of a disease and its persistence in soil. There is no fixed pattern by which organic matter exerts its effects on the different kinds of pathogens present. If it serves as a direct food source for the disease organism it may increase disease intensity; if it acts as a source of nutrients for the host it may build up resistance to the disease organism; and if it increases the growth of competing organisms it may suppress the disease. These and other possibilities are discussed below for the five kinds of pathogens mentioned above. The soil is such a complex environment, both biologically and non-biologically, that consistent results of a given treatment are not always obtained.

The experimental difficulties involved are well expressed by Wilhelm (1959). He states: "Below ground we deal frequently not with straightforward parasite–host-disease relationships amenable to ready experimental check as in above-ground pathology, but with the still somewhat unconventional pathology where a recognized invader may not be the cause of disease, and where an outsider may. Nowhere, as in the soil, are plant parts and organisms bathed in each other's metabolites, those secreted by the plant providing conditions selective for certain soil organisms, and those of the soil organisms thus selected having injurious as well as salutary effects upon the plant."

Fungi

Most root-rot diseases are caused by fungi that live continuously below the soil surface, either in the roots of their host or on organic residues. There are many kinds of these organisms that affect plant growth, and their growth habits vary widely. They may be obligate parasites on the one hand, and strictly nonpathogenic on the other with all intermediate gradations. Added to these features are the many interactions that occur between fungal species, and in fact between many other organisms present in the soil-root environment.

Obligate parasites are those that grow only on living plant tissues and are completely lacking in saprophytic abilities. When the host plant dies the fungus would also die were it not for the fact that they commonly produce resting spores or sclerotia that can live in the soil for a few months, or sometimes years, in a dormant state. Such structures enable the organisms to survive until a new host plant is growing on the soil.

Information on the time of survival of these obligate parasites is now uncertain because some of them can grow on the roots of plants other than their usual host, and may or may not produce visible lesions. If there is no visible evidence of the presence of the pathogen on a non-host plant, such as a weed, it is extremely difficult to detect the presence of the parasite. It is possible and probable that some obligate parasitic fungi feed on the exudates from non-host plants and by this means obviate the necessity for root penetration in order to survive.

One of the more common ways of testing for survival of a pathogenic fungus is to merely grow a susceptible crop on the soil and observe the degree of root infection. This practical method may lead to very serious errors in survival data if the fungus can continue to live on foreign hosts, especially when there is no certainty as to what plants, if any, are helping to prolong the survival period.

Another type of fungal pathogen is one that is strongly parasitic but can grow, or at least continue to live saprophytically, on the dying and dead tissues of its host. Its growth vigor as a saprophyte is usually very weak but it can continue to live in ever-decreasing numbers in the tissues that it originally invaded parasitically. The survival time in this case is likely to be limited but at least a few cells may be able to survive in the dead host tissues until another season and fresh young host plants are available for colonization. If such a parasite also produces dormant bodies then survival is primarily dependent upon these and not on any continued saprophytic growth in dead hosts.

The next state in the pathogen–host relationship is the fungi that are primarily saprophytes but also possess weak parasitic ability. They are very common in soils where they live on readily decomposable organic matter but may or may not attack living plant roots. Their parasitic ability is most likely to be manifest when plants are weakened for any reason, such as poor nutrition or attack by organisms that have stronger parasitic ability. Often several species of fungi and other organisms are involved simultaneously. Most of these organisms are considered as common soil-inhabiting organisms and are nearly always found in reasonably normal soils. Survival is no problem with these organisms because they produce spores abundantly that may be able to survive in soil for years.

Finally, there are the masses of saprophytic fungi in soil that are not classified as parasitic although they may through competition for food supplies, by antibiotic production, or through other poorly understood mechanisms make conditions in soil unfavorable for plant growth. They produce plant symptoms that differ little from those produced parasitically by other fungi. Under some conditions, such as where fresh organic matter is abundant, they may by one or more mechanisms produce considerable plant injury. Under other conditions striking benefits may be realized through suppression of the growth of the strongly parasitic fungi, or by destruction of dormant structures.

These fungi covering the range of obligate parasitic to completely saprophytic are not to be considered as fixed stable groupings of organisms. There are all degrees of pathogenicity which constantly change via selection, adaptive enzymes, and through genetic changes. This is not unlike the well-known cases where insects gradually acquire resistance to certain insecticides, such as DDT, and bacteria may lose their susceptibility to antibiotics, such as penicillin. In nature, life always seems to be in a state of change as the environment changes; one strain of plant or animal is replaced by another that is more suited to the new conditions.

The concept of inoculum potential is one that has been much discussed in recent years (Garrett, 1960; Dimond and Horsfall, 1965) and needs to be considered here in connection with pathogenic fungi that have considerable ability to live as saprophytes. As Garrett points out, the invasion of a host root and the establishment of a progressive infection requires a certain amount of energy by the fungal parasite to overcome both passive and active host resistance. This required potential he defines as "the energy of growth of a fungal parasite available for infection of a host at the surface of the host organ to be infected." Inoculum potential may be increased either by increasing the number of infecting units or propagules of the fungus per unit of root surface, or by increasing the nutritional status of such units. If an individual infecting unit is inadequate for the establishment of a progressive infection then multiple invasion may do so as a result of the synergetic effect.

Under any given set of environmental conditions, the concept of inoculum potential of a parasite states that there must be a limiting value below which establishment of the infection will not occur. The food base that supplies the necessary energy and nutrients for building up the inoculum potential ordinarily comes from dead infected host tissue permeated with mycelia. Where sclerotia are produced, they may also serve as the food base. Likewise, crop residues and other forms of decomposing organic matter may serve as the energy base for building up the inoculum potential provided that the fungus can utilize the energy in such substances. Although Garrett stresses the importance of inoculum potential in infection he also points out that this is only one factor involved; infection may fail to occur for many other reasons. Similarly, Dimond and Horsfall (1965) state that the ability of a pathogen to infect its host is conditioned by the amount and virulence of the inoculum, the environment, and the susceptibility of the host.

The above discussion of inoculum potential is given here to show that at least under one set of conditions the addition of organic residues, if utilizable by the pathogen, can increase the incidence of plant disease. Fortunately, under most other conditions that are discussed below, the opposite effect is far more common.

Actinomycetes

The actinomycetes constitute a large and diverse group of microorganisms that inhabit the soil. They apparently produce no spores but live saprophytically, producing masses of mycelia where there is an adequate and suitable supply of active organic matter. There are only two important plant diseases produced by them, namely potato scab and sweet potato pox. These disease organisms readily persist in the soil and can be considered as soil organisms. Since these two pathogens can live on the roots of plants other than their usual hosts, there is much doubt as to the length of time that they can survive in uncropped soil; they undoubtedly also possess considerable saprophytic ability. Actinomycetes are also antibiotic producers and are sensitive to antibiotics.

The turning under of certain green manure crops has in some instances resulted in a reduction in the incidence of potato scab (Rouatt and Atkinson, 1950; Wood and Tveit, 1955). One explanation offered for this was that the green manure increases the growth of other organisms that compete strongly with the pathogen. The full answer is not yet known. Certainly the nonpathogenic saprophytes would under such conditions compete for food, and they would also produce antibiotics. But the green manure crop might also increase the resistance of the host by supplying nutrients to it. Furthermore, a green manure crop may affect the physical and chemical environment in the soil as, for example, by changing the pH, increasing soil CO_2 content, and reducing the oxygen percentage. This is a good example of how a single change in cropping procedure can markedly affect the whole ecology.

Bacteria

The bacteria that are pathogenic to plants live a saprophytic existence in soil when they are not growing on their hosts. According to Menzies (1963) none of them is an obligate parasite, and their saprophytic abilities vary widely. They usually gain entrance to the soil through infected plant tissues. Since most species do not form spores, their ability to survive is usually less than that of fungi. Little is known about their methods of survival but it is assumed that they remain in the soil in the vegetative state where the death rate usually greatly exceeds the rate of formation of new cells. Only a few species are persistent soil inhabitants.

The importance to pathogenic bacteria of organic residues in soil other than the dead tissues of the plants attacked by the bacteria is not fully known. Certainly some of these organisms can obtain their energy from these residues but considering the speed with which most of them die it seems probable that this is not a very satisfactory food source. In fact, Burkholder (1948) states that none of the species has been shown to attack cellulose, and only a few can hydrolyze starch. Some of them live on the roots of plants that they do not attack parasitically. Since they all live in close association with other common soil inhabitants it is likely that they make use of bits of substances formed by this mass of soil saprophytes. Such an associative action could account for the survival of the few bacterial pathogens that have been shown to persist for two or more years in uncropped soils.

Crop residues may also play a role that is the reverse of that described above; they are the food source for many saprophytes that produce antibiotics that can inhibit the growth of the bacterial pathogens. This could account in many cases for short-time survival of the pathogens present as vegetative forms. As emphasized in a previous chapter, the concentration of antibiotic produced is very important. At very low concentrations it might stimulate bacterial growth or at least have little effect, whereas at higher levels it might kill nearly all organisms. Since high levels would occur where the antibiotic-producing organisms have an abundant food supply, this is a situation where crop residues should help to control any bacterial parasites that are present and susceptible to the antibiotics being produced. It is likely that this is one of the chief mechanisms that nature uses to stabilize the microbial ecology under any given set of conditions. It is well-known that inoculations of soil with a foreign bacterial species seldom results in heavy colonization of the soil by this outside organism. Pathogenic bacteria that gain entrance to soil via diseased plant tissue may meet the same fate. Those organisms, such as the ones that produce soft rots or crown galls, may be able to persist in soils indefinitely because of the absence of inhibitors that are effective against them. Even if such inhibitors are produced, the amount may be too low for effective killing, or there may be pockets where high and low concentrations exist.

Viruses

Viruses are obligate parasites and most have no method of surviving except in infected plants or in their vectors – the agents responsible for introduction of the viruses into plants that were previously virus-free. A succession of susceptible crops, especially biennials or perennials, grown near annuals, will permit a virus disease to continue to thrive on annual crops year after year. An air-borne virus, and probably also the soil-borne ones, may have several hosts and the effect on these may vary widely. A virus may also undergo changes in characteristics when transferred from one host to another. According to Cadman (1965), soil-borne viruses, like the air-borne ones, probably have no existence in soils apart from the organisms that transmit them and the plants that they infect. He states that "many kinds of soil inhabitants seem well fitted to act as virus vectors, but so far ectoparasitic nematodes and chytrid fungi (represented by *Olpidium brassicae*) are the only groups implicated."

Ectotrophic nematodes are those that feed superficially on plant roots but move about freely in soils. They puncture cell walls of root tips by means of their mouth spears. Root malformations, such as galls or stubby roots, may or may not be observed but regardless of this, plant growth is likely to be seriously inhibited. The first soil-borne plant virus shown to be carried by a nematode vector was grapevine fanleaf (Hewitt et al., 1958) but a number of other such viruses that produce diseases in a variety of crops have since been shown to have nematode vectors. The association between nematode species and the viruses that they transmit is very specific but the host range may be wide. The vectors commonly retain the viruses for several weeks or months in the absence of host plants. Nematode viruses are usually transmitted through the seeds of many plants that they infect.

Lettuce plants have been shown to become infected with big-vein virus when their roots become parasitized by zoospores of *Olpidium brassicae* released from the roots of infected lettuce plants. Presumably, according to Cadman (1965), the zoospores carry the virus internally and the evidence suggests that the virus survives within resting sporangia, even when they are stored dry. Other soil-borne viruses are undoubtedly transmitted in a similar manner by chytrid fungi but positive proof of this is not yet available. These viruses that are transmitted by chytrid fungi are not, so far as known, seed-borne in their hosts.

Soil organic matter is not known to play any appreciable role in either the spread or control of air-borne virus diseases. This is an obvious statement since these viruses are obligate parasites on green plants and the vectors are insects. There is more likelihood that soil organic matter plays a role, even if a minor one, in soil-borne virus diseases since the vectors are nematodes, fungi and probably other forms of life that feed in part on decaying crop residues.

Since decaying organic matter is known to provide a favorable environment for the multiplication of nematodes and fungi it is possible that such organic material might even act to increase virus damage. There is no certainty that this would happen, however, for organic matter might also favor the growth of organisms that are antagonistic to the vectors. The predacious fungi, for example, that attack nematodes would be an outstanding example (Duddington, 1957). These could attack only the ectoparasites. The growth of masses of fast-growing saprophytic fungi and bacteria may also inhibit the growth of virus-carrying fungi, such as *Olpidium brassicae*. In addition, decaying organic matter would release nutrients that might make the host plants more resistant to infection.

Any possibilities along these lines will have to await future research. Fortunately, there are methods of control of these diseases having little relation to soil organic matter that appear to be promising (Cadman, 1965).

Nematodes

Nematodes constitute one of the largest and most ubiquitous groups of the animal kingdom; they are the dominant worms in soil if bulk and pedological effects are ignored (Christie, 1959; Kevan, 1965). Most species of nematodes are found in soil, including those parasitic on animals as well as the comparatively few species that are parasitic on plants. They are free-living organisms that require at least a thin film of moisture for growth but by means of cysts or eggs can withstand drought (see Chapter 4).

The foods of nematodes vary widely and include small forms of plant and animal life, including other nematodes and rotifers (Boosalis and Mankau, 1965). Some species are known to feed on decaying organic matter but there is uncertainty as to the extent this occurs. Other species are associated with plant roots, where they may directly or indirectly cause injury. Often they are associated with other organisms that are injurious.

Plant-parasitic nematodes commonly exist in three forms or positions which Mountain (1965) considers as stages in their evolution. Some genera are ectoparasites that feed on the epidermis or cortex causing cell necrosis, others exhibit migratory endoparasitism, and the third group is sedentary endoparasitic. In sedentary endoparasitism, which is restricted to the female, there is morphological adaptation and a high rate of reproduction. There is also a development of distinct feeding areas with specific plant responses and marked suppression of cell necrosis. Mountain states that the trend from ectoparasitism to sedentary endoparasitism is usually associated with an evolution toward a balanced host–parasite relationship.

Injuries to plants that are commonly attributed to nematodes are often the result of the combined action of these organisms with microflora, either soil-borne viruses, fungi or bacteria. Studies indicate that complex synergistic relations exist between nematodes and parasitic microflora, but these relations have not yet been clearly defined. Nematodes can at least penetrate cells and thus expose them to attack by bacteria and fungi that otherwise might not be able to gain entrance. Reference to their action as vectors for viruses was made in an earlier section.

The role of organic matter in either the spread or suppression of plant parasitic nematodes is largely unknown, as in the case of virus diseases. Since nematodes need a food supply, oxygen, and a water-film in which to grow one might suspect that organic matter would favor the growth, but here, again, the organic matter is also favoring many other kinds of organisms that may inhibit nematode multiplication. It is fortunate that most species of nematodes are not parasitic on plants. It is just possible that organic matter might favor the nonparasitic species at the expense of the disease-producers. There is much need for scientific evidence on the interrelationships of the soil microflora and fauna.

Fungi that prey on nematodes

More than 50 species of predacious fungi have been described (Boosalis and Mankau, 1965). It is almost unbelievable that these fungi with hyphae about 2 to 8 μ in diameter can capture nematodes having diameters 100 or more times greater, and masses several thousand times greater. It is even more amazing when one bears in mind that nematodes are very active and powerful for their size, and thrash about with great force. As Duddington (1957) says, it is no mean feat for these fungi with such delicate mycelia to trap such giants.

The fungi have numerous ingenious ways of catching nematodes (Duddington, 1957). These include adhesion to the hyphae, constricting and nonstricting rings of hyphae, networks of adhesive branches, and sticky knobs. Capture is commonly accomplished by means of specialized hyphae that are coated with an adhesive, but in other instances mechanical force alone is used. When constricting rings are involved, the rings close very quickly on the nematode as soon as it touches the inner surface of one of the cells of the ring. This closing is apparently triggered by a substance formed by the nematode. In some species infection of the host is by means of a spore that either sticks to the exterior of the nematode on contact, or is ingested. Those that adhere to the outside penetrate it by means of a germ tube, and then form a mycelium within the animal. The mycelium grows at the expense of the body of the host, eventually kills it, and sends up aerial hyphae on which small spores are formed in profuse numbers. Duddington describes in considerable detail the mechanisms used by nematode-eating fungi in attacking their victims.

Predacious fungi are found widely distributed in soils, composts, manures, rotten wood, and decaying vegetation. Many of them are not obligate predators but can grow saprophytically under widely varying conditions. Fungi commonly form traps only when nematodes are present, indicating the need for a triggering substance. Their victims seem to be selected by chance contact. Captured nematodes struggle for a while but soon become quiet, and the fungus then ramifies throughout the animal and absorbs its contents. Death may be hastened by a toxic secretion of the fungus, but this has not been proven.

Only a limited amount of work has been done on the control of pathogenic nematodes by means of predacious fungi. Duddington (1957) states that some species can effectively exterminate the nematodes in a plate culture in a few days, but their effectiveness under field conditions is still uncertain. There is evidence that the addition of organic matter to field soils increases nematode-trapping fungi for a short time at least, and decreases nematode damage, but proof that such benefits are the result of increased activity of the fungi has not been reported. Such research is handicapped by lack of a suitable method for the enumeration of the predacious fungi. In addition, the whole field of microbial ecology is involved and the interactions between all soil organisms and their environments must be considered.

BIOLOGICAL CONTROL OF SOIL-BORNE PATHOGENS

Biological control of a plant disease has been defined by Garrett (1965) as "any condition under which, or practice whereby, survival or activity of a pathogen is reduced through the agency of any other living organism (except man himself) with the result that there is a reduction in incidence of the disease caused by the pathogen. Biological control can be brought about either by introduction or by augmentation in numbers of one or more species of controlling organisms, or by a change in environmental conditions designed to favor the multiplication and activity of such organisms, or by a combination of both procedures."

There is probably no other constituent or factor in cultivated soils that is more important than organic matter in favoring the development of organisms that suppress the multiplication and activity of soil-borne pathogens. The forms of organic matter that are most active in this respect are green manures, crop residues, animal manures, and growing plants. Hence, in this sense, crop rotation can be a major factor in the biological control of plant disease organisms that normally inhabit the soil. The discussion that follows will deal chiefly with the overall direct and indirect effects of organic matter on soil-borne plant diseases. Reference has already been made to some of the specific effects of organic matter on the different types of pathogens involved.

Inoculation with antagonistic organisms

Soil microbiologists determined at an early date that it is seldom possible to introduce an outside organism into an unsterilized soil and have it thrive there. This is because most organisms that can grow in soils are already there. As previously emphasized, there are thousands of all kinds of organisms in all soils and each must come to terms with the others. Each species is literally fighting for its life if it is in the vegetative stage; if not, it is there in some sort of a resting stage waiting for the opportunity to come to life and assert itself. This is nature in the raw, otherwise known as microbial ecology. With such keen competition, and usually very deficient food supply, it is scarcely surprising that the introduction of an outside, or exotic, organism seldom leads to appreciable multiplication.

Regardless of these basic facts, many attempts were made by plant pathologists to introduce pure cultures of vigorous saprophytes into soil for the purpose of suppressing diseases. Except where soils had been sterilized and reinoculated with the pathogen, the added saprophyte seldom if ever thrived for more than a brief period. Only by changing the soil itself can a higher population of the added saprophyte be expected to persist.

Garrett (1955) in very expressive words summed up the situation, and emphasized how unsuccessful inoculation experiments have been. He stated that "the marriage between plant pathology and soil microbiology, now consummated, was followed by a honeymoon period of unbounded optimism, during which the most extravagant hopes were entertained for the progeny of the union, to be christened "Biological Control". The first optimistic forecasts of the prospective god-parents, amongst whom I was one, were dimmed by anxiety when it was eventually realized that the pregnancy would be unexpectedly long and difficult. One child, indeed was still-borne, and was quietly laid to rest under a tombstone inscribed Biological Control by Inoculation of the Soil with Antagonistic Microorganisms', though some of the bereaved claim that it was buried alive and is, in fact, still faintly breathing. Other children of the marriage, though at first puny, are yet alive and slowly progressing, and more promising ones will assuredly be born in due course."

Garrett's present views, so far as I know, have not changed with respect to his evaluation of inoculation of soil with antagonistic microorganisms for disease control. With regard to the broader field of biological control he (Garrett, 1965) emphasizes that this is an endless series of individual problems in applied microbial ecology, but believes that "eventual prospects for biological control are brighter than ever before, partly because we can at last comprehend the magnitude of the problems to be solved."

Green manures and crop residues

The addition of comparatively large amounts of green manures or crop residues to soil is one of the most effective ways of changing the habitat to permit a change in the total and relative numbers of soil organisms.

Previous mention was made of the success obtained in the control or partial control of potato scab and take-all disease of wheat by the addition of green manures. Considerable success has also been obtained in the curtailment of *Phymatotrichum* root rot of cotton. More recent additions to the list are root- and foot-rot diseases of snap beans caused by *Rhizoctonia solani* and by *Fusarium solani* f *phaseoli*, respectively. The effectiveness of control of these diseases depends on many factors, especially the soil and the organic amendment added.

The addition of green manures or crop residues, according to Garrett (1965), may affect a root disease in the following three ways: (1) by a direct effect on the activity of the parasite; (2) by a direct effect on the survival of the parasite; and (3) by an indirect effect on parasitic activity on the roots through the effect on host resistance resulting from the release of plant nutrients. This third suggested possibility should be modified to include immobilization as well as release of plant nutrients, chiefly nitrogen. The first of these three ways is commonly the most important.

From the early work with the take-all diseases of cereals Garrett concluded that organic manuring contributes to disease control by raising the carbon dioxide content in the root zone, which in turn suppresses ectotrophic growth of the fungus on the roots. Survival of the pathogen in infected stubble is reduced by organic amendments with wide carbon–nitrogen ratios because on decomposition they take up nitrogen from the soil and reduce the supply to the fungus. Organic materials may also release available nitrogen and phosphorus that stimulate root growth and host resistance. Garrett did not mention the possible role of increased antibiotic production following the addition of organic amendments but in the light of subsequent research this possibility cannot be ignored.

The control of root-rot of cotton by heavy dressings of green manures and animal manures is attributed primarily to the effect that they have in increasing the germination of the sclerotia of *Phymatotrichum omnivorum* in the absence of any host–root stimulus. Control of this disease by the use of green manures is not always successful, and, as in other diseases, there are many factors involved that affect the results. Nevertheless, when conditions are right, organic amendments can markedly reduce losses caused by this pathogen under field conditions.

The effect of nitrogen-deficient organic amendments in checking the *Rhizoctonia* disease of snap beans has been attributed largely to the increase in carbon dioxide in the soil air and to the scarcity of available nitrogen that occurs during decomposition. The hypothesized effect of carbon dioxide certainly needs further investigation before this explanation can be accepted. In the case of foot- or root-rot disease of snap beans it has also been shown that the addition of nitrogen-deficient plant materials does curtail the disease whereas green manure crops increase the incidence of the disease. Similar effects would not necessarily be obtained with other pathogens with different degrees of parasitic and saprophytic activity, and possibly less sensitive to carbon dioxide.

Much work has been done on the control of the group of diseases caused by *Rhizoctonia solani* using antagonistic organisms and various organic amendments added to sterilized and unsterilized soil. Wood and Tveit (1955) summarized this work and concluded that many soil organisms are antagonistic to this pathogen, and that some are able to control the disease when sterilized soil is used as the culture medium. The few studies conducted under field conditions have usually yielded negative or uncertain results. The addition of organic amendments to field soils has usually given better results than the use of antagonistic organisms selected by pure culture techniques. Erratic results with these amendments are, however, not unusual. The mechanisms of antagonism are discussed by Boosalis and Maukau (1965).

Considerable research (Davey and Papavizas, 1963; Papavizas, 1963) has been done in the U.S. Department of Agriculture in recent years on the suppression of plant diseases by means of additions of organic matter. Oat straw, or straw with small amounts of ammonium nitrate, increased the numbers of rhizosphere microorganisms antagonistic to *Fusarium solani, F. phaseoli, Rhizoctonia solani, Thielaviopsis basicola*, and *Verticillium albo-atrum.* Ammonium nitrate in large amounts, however, decreased the numbers of bean rhizosphere antagonists, especially in very acid soils. These antagonists in acid soil consisted largely of bacteria, whereas in near neutral soils streptomycetes were predominant.

Diseases caused by *Phytophthora* and *Pythium* spp. resemble closely in their development those caused by *Rhizoctonia solani*, and in general experiments on control have yielded similar results. Many soil organisms are antagonistic to these pathogens but seldom are they effective except in laboratory or sterilized soil cultures.

Fungistasis

Attention has been given in this and other chapters to the general subject of antagonisms as a factor in disease control, and in the whole ecology of a soil. Antagonism, as already emphasized, involves competition for nutrients, space and air among the large number of heterogeneous organisms found in soil. Antagonism also involves dealing with end products of metabolism excreted by other organisms, including antibiotics, carbon dioxide, organic acids, etc. In a more direct and individualistic way antagonism also includes parasitism and predation. One aspect of this subject, seldom mentioned and little understood, is fungistasis (Dobbs et al., 1960; Park, 1960; Jackson, 1965). The term fungistasis, as commonly used, refers to inhibition of spore germination. The inhibition may, however, include retarded or limited vegetative growth and intensity of sporulation.

During the period since about 1953 it has been established that the spores of most, or at least many, fungi do not readily germinate in soil unless stimulatory substances liberated by living plant roots and organic residues are present. Lack of germination is not usually due directly to a deficiency of nutrients although in some studies it has been shown that the addition of glucose to soil will overcome the inhibition of germination of certain fungal spores. It has also been shown that growing bacteria and actinomycetes can stimulate fungal spore germination, and also that alcohol extracts of certain kinds of fungal spores will either stimulate or inhibit bacterial growth, depending on the concentration.

Jackson (1965) states that "there is, as yet, no clear evidence of the origin or nature of soil fungistasis." Under some, but not all, conditions there is evidence that antibiotics play an important role in fungistasis. The suggestion has also been made that aromatic compounds formed during the degradation of lignin may be involved in fungistasis. A more general postulate is that both toxic metabolites and the general saprophytic activities of the soil microflora are involved.

More exact information on the nature of fungistasis has been presented by Menzies and Gilbert (1967) and Gilbert and Griebel (1969). They showed that the exposure of soil to volatile organic substances released from alfalfa hay, corn leaves, wheat straw, bluegrass clippings, tea leaves, and tobacco induces an immediate increase in the rate of respiration. Semidormant bacterial populations are increased and the fungi are stimulated to produce visible growth on the soil surface. The new fungal growth was oriented toward the source of the volatile material. These neutral organic stimulants were not identified but were shown to be water- and acetone-soluble, and distillable. The authors were of the opinion that they were acting primarily as respiration growth stimulants and not as food sources.

These findings would seem to have considerable significance in connection with the control of plant diseases. They help to explain at least one of the mechanisms by which organic residues often reduce disease intensity. When such materials overcome fungistasis they stimulate the dormant pathogenic fungi to vegetative growth and possibly to more rapid disappearance from the soil at a time when no host plant is present. The effect could well be superimposed upon any antagonistic effects between the pathogen and its natural antagonists, especially competitive saprophytic soil microorganisms that may also produce antibiotics or other growth-inhibiting substances.

Rhizosphere microorganisms in relation to root infection

The root surfaces of healthy growing plants are covered by a mass of microorganisms, mostly heterotrophic bacteria, as is pointed out in Chapter 5. At specific locations, where the amount of root exudate is greatest, the root surface is literally covered by a film of bacteria. The numbers here may be ten, twenty, or even a hundred times greater than in the same soil a few millimeters distant. Experimental data have shown that often as much as half of the carbon dioxide given off from plant roots is actually produced by the microflora present on the roots. This has been demonstrated by growing plants under sterile and nonsterile conditions. This mass of heterotrophic microorganisms at the exact points where pathogenic organisms have to attack the roots to gain entrance plays a major role as antagonist against these pathogens. This antagonism is exerted primarily through competition, defined in its broadest sense, through plant-produced toxins, and through antibiotics. A fair estimate is that at least a third of the nonpathogenic organisms in the rhizosphere are producers of one or more antibiotics.

Rhizosphere microfloras differ greatly between different kinds of plants, different ages, different parts of the root system, and between plants grown under different environmental conditions. The composition of the flora may also change as conditions change and as the amount and composition of the root exudate changes. It is pointed out in the previous chapter that many plants produce substances that are inhibitory to other higher plants and to some microorganisms. Others produce substances, such as amino acids, that are needed for the growth of some bacteria and fungi. Even antibiotics produced by one rhizosphere microorganism may act as stimulants to the growth of certain others so long as the concentration is very low. These various effects of one organism, whether higher plant or microorganism, on others can range from extreme toxicity to one organism to synergistic to another. Hence, the wide and changing variations in the composition of the microflora populations. Obviously, plant pathogens are subject to these same environmental factors and it is not at all surprising that some of them are known to be suppressed to the extent that plant infection is either prevented or greatly curtailed. As Garrett says, this would not necessarily mean that all growth of the pathogens is prevented but merely that the inoculation potential is too low because of competition with saprophytes, toxic substances, or for other reasons not yet well understood. As he says, the rhizosphere and the root surface microfloras appear to constitute the outermost defense barrier against invasion by pathogenic fungi.

What effect do organic amendments applied to soil have upon the nature of the microflora on the root surface? The answer to this question is of considerable interest considering that green manures and crop residues serve to reduce the severity of some diseases. Present evidence indicates that such materials have only a minor effect on the rhizosphere population, and hence any disease curtailment that they bring about must be attributed to other mechanisms. This lack of effect on the root surface flora is not surprising considering that these organisms are being well-fed by root exudates. Furthermore, the added organic amendments are seldom in intimate contact with the roots. Time is also a major factor since amendments added during the warm growing season are largely decomposed within 4 to 8 weeks. Even if the seeds are planted at the time of addition of the organic amendment, which is often a hazardous practice, the big flush of biological activity is largely completed before the seedlings have developed much of a root system. Biological control of plant diseases via changing the root surface through organic matter additions does not, therefore, appear to be very promising.

Crop rotation

The agronomic practices followed in the growing of crops often markedly affect the extent of damage caused by diseases of these crops. Probably the most important of these practices, aside from the addition of organic matter, is crop rotation. Other important cultural practices include tillage, fertilization, and sanitation. In her discussion of crop sequence in relation to soil-borne pathogens Glynne (1965) concludes that "few methods of biological control seem to offer such rich rewards in terms of increased yield of individual crops and increased productivity of land as does the use of crop sequence to control soil-borne pathogens."

Crop rotation bears a close relationship to the title of this book since the crops grown, and the disposal made of them, affect the quality and quantity of organic matter in soils, and the extent of disease control. Nevertheless, the subject is in a sense a side issue and involves such a mass of research that no attempt will be made here to discuss it at length. Fortunately, Curl (1963), in a 67-page paper with 479 references has done an excellent job of assembling and analyzing the data. In addition, Kincaid (1960) has reviewed the information on the diseases of tobacco and states that some of those caused by nematodes, fungi, bacteria and viruses are amenable to control by crop rotation.

A study of Curl's paper serves to emphasize that few general statements can be made with respect to the effect of crop rotation on disease control. There is an almost endless number of diseases, soils, crops, climates, flora, fauna, fertilization treatments, culture systems, etc., each of which has a bearing on disease control, and on the whole subject of microbial ecology. Curl gives an excellent discussion of the principles and mechanisms involved in disease control by crop rotation. His review shows that rarely can crop rotation be used as a means of completely eliminating a disease, but frequently marked reduction in damage can be realized. This is most commonly brought about by a marked reduction in the number of disease-producing organisms in the soil following the growing of one or more crops that do not serve as hosts for the disease organism. Bare cultivated fallows may also serve to curtail diseases through elimination of host plants and by killing many pathogens following the drying out of the soil. An effective rotation on one soil may not be satisfactory on another, or even on the same soil under different climatic conditions. Likewise, different rotations are needed for different crops. These findings are not surprising, considering the myriad of factors involved. Regardless of this, crop rotation has been used for fertility and disease control since the Roman era and, as Glynne says, is still one of the best nonchemical methods of disease control.' By making use of green manures, crop residues, and crop rotation much can be done toward the control of many, but not all, of the more troublesome diseases. Eventually we can hope that plant varieties that resist diseases can be developed but it is unlikely that such varieties will be able to resist all diseases. Plant breeders have already achieved marked success in the production of new varieties of various crops that are resistant to specific diseases.

ECOLOGY AND PLANT DISEASE CONTROL

This comparatively brief discussion of the role of organic matter in disease control emphasizes how little we know about the subject, and the difficulties of conducting research in this field. This is because we must deal, ultimately at least, with the whole field of ecology that involves all living organisms present in and on the soil, all factors that materially affect them, and the transformations that are brought about by them or independent of them. Ecology is defined by Webster as: "(a) the branch of science concerned with the interrelationship of organisms and their. . . community development and structure, interaction between different kinds of organisms, geographic distributions, and population alterations, and (b) the totality or pattern of relations between organisms and their environment."

When the subject of ecology, or more specifically, microbial ecology, is mentioned most of us think of kinds of organisms and some of the reasons why certain ones thrive and others are scarce or non-existent in a given community. This is all very well but as biological sciences have advanced we have had to think more and more in terms of the biochemical transformations brought about by the organisms. It is these invisible changes that are frequently chiefly responsible for the particular species that thrive in a given environment, and those that disappear or perhaps pass into dormant forms. Alexander (1964) has discussed at some length some of the chief ways in which these biochemical processes manifest themselves. He also stresses the present dearth of knowledge and pleads for more intensive fundamental research in this field using an in vivo rather than an in vitro approach to the subject. This is the information that is needed but the difficulties and pitfalls are great. If the usual basic method of conducting research, which consists in isolating the factor that is to be studied, is applied to the study of biochemical ecology the results usually have no meaning when applied to field conditions. If, instead, we study all factors as a unit it is likely that the results cannot be interpreted with certainty and cannot be repeated consistently. The whole picture is certainly not hopeless but progress will necessarily continue to be slow and will involve a continued whittling away at the subject using each new tool or method as it is made available by scientists in this and allied fields of research.

In commenting on the unsatisfactory state of our knowledge of mycoparasitism obtained largely by means of dual-culture studies in vitro, Boosalis and Mankau (1965) state that "this does not mean that studies in vitro should be discontinued. On the contrary, it points up the need for more basic work in vitro to elucidate the physiological and biochemical mechanisms of parasitism and to show how their mechanisms relate to susceptibility of the host fungus in response to environment." These studies would be followed up by studies in natural soils. This viewpoint seems most logical to the writer.

REFERENCES

Alexander, M., 1964. *Ann. Rev. Microbiol.*, 18: 217–252.

Baker, K.F. and Snyder, W.C., 1965. *Ecology of Soil-borne Plant Pathogens.* Univ. Calif. Press, Berkeley, Calif., 571 pp.

Bawden, F.C., 1957. In: R.E.O. Williams and C.C. Spicer (Editors), *Microbial Ecology.* Cambridge Univ. Press, London, pp. 299–314.

Boosalis, M.G. and Mankau, R., 1965. In: K.F. Baker and W.C. Snyder (Editors), *Ecology of Soil-borne Plant Pathogens.* Univ. Calif. Press, Berkeley, Calif., pp. 374–391.

Burkholder, W.H., 1948. *Ann. Rev. Microbiol.*, 2: 389–412.

Cadman, C.H., 1965. In: K.F. Baker and W.C. Snyder (Editors), *Ecology of Soil-borne Plant Pathogens.* Univ. Calif. Press, Berkeley, Calif., pp. 302–313.

Christie, J.R., 1959. *Plant Nematodes – Their Bionomics and Control. Agric. Exper. Stn., Univ. Florida, Gainesville, Fla.*, 255 pp.

Curl, E.A., 1963. *Bot. Rev.*, 29: 413–479.

Davey, C.B. and Papavizas, G.C., 1963. *Soil Sci. Soc. Am., Proc.*, 27: 164–167.

Dimond, A.E. and Horsfall, J.G., 1965. In: K.F. Baker and W.C. Snyder (Editors), *Ecology of Soil-borne Plant Pathogens.* Univ. Calif. Press, Berkeley, Calif., pp. 404–419.

Dobbs, C.G., Hixon, W.H. and Bywater, J., 1960 In: D. Parkinson and J.S. Waid (Editors), *The Ecology of Soil Fungi.* Liverpool Univ. Press, Liverpool, pp.130–147.

Drechsler, C., 1937. *Mycologia*, 29: 447–552.

Duddington, C.L., 1957. In: R.E.O. Williams and C.C. Spicer (Editors), *Microbial Ecology.* Cambridge Univ. Press, London, pp. 218–237.

Garrett, S.D., 1955. *Ann. Appl. Biol.*, 42: 211–219.

Garrett, S.D., 1960. *Biology of Root-infecting Fungi.* Cambridge Univ. Press, London, 293 pp.

Garrett, S.D., 1965. In: K.F. Baker and W.C. Snyder (Editors), *Ecology of Soil-borne Plant Pathogens.* Univ. Calif. Press, Berkeley, Calif., pp. 4–17.

Gilbert, R.G., and Griebel, G.E., 1969. *Soil Sci. Soc. Am., Proc.*, 33: 270–273.

Glynne, M.D., 1965. In: K.F. Baker and W.C. Snyder (Editors), *Ecology of Soil-borne Plant Pathogens.* Univ. Calif. Press, Berkeley, Calif., pp. 423–435.

Hewitt, W.B., Raski, D.J. and Coheen, A.C., 1958. *Phytopathology*, 48: 586–595.

Jackson, R.M., 1965. In: K.F. Baker and W.C. Snyder (Editors), *Ecology of Soil-borne Plant Pathogens.* Univ. Calif. Press, Berkeley, Calif., pp. 363–373.

Kevan, D.K.M., 1965. In: K.F. Baker and W.C. Snyder, (Editors), *Ecology of Soil-borne Plant Pathogens.* Univ. Calif. Press, Berkeley, Calif., pp. 33–51.

Kincaid, R.R., 1960. *Bot. Rev.*, 26: 261–276.

Menzies, J.D., 1963. *Bot. Rev.*, Jan.–March: 79–122.

Menzies, J.D. and Gilbert, R.G., 1967. *Soil Sci. Soc. Am., Proc.*, 31: 495–496.

Mountain, W.B., 1965. In: K.F. Baker and W.C. Snyder (Editors), *Ecology of Soil-borne Plant Pathogens.* Univ. Calif. Press, Berkeley, Calif., pp. 285–301.

Papavizas, G.C., 1963. *Phytopathology*, 53: 1430–1435.

Park, D., 1960. In: D. Parkinson and J.S. Waid (Editors), *Ecology of Soil Fungi.* Liverpool Univ. Press, Liverpool, pp. 148–159.

Rouatt, J.W. and Atkinson, R.G., 1950. *Can. J. Res. Sect. C*, 28: 140–152.

Wilhelm, S., 1959. *Plant Pathol. Probl. Prog.*, 1908–1958. Univ. Wisc. Press, Madison, Wisc., Ch. 32: 356–366.

Wood, R.K.S. and Tveit, M., 1955. *Bot. Rev.*, 21: 441–492.

SOME ORGANIC MATTER AND CROP MANAGEMENT PROBLEMS IN MINERAL SOILS

Chapter 20

ORGANIC MATTER IN THE DEVELOPMENT OF AGRICULTURAL SOILS

INTRODUCTION

An agricultural soil may be defined as one that is capable of producing good yields of a variety of crops indefinitely under conditions of good farm management, including the use of suitable cropping systems, fertilizers, animal manures, and lime as needed. Such a soil should ideally be well drained, have good tilth, be of adequate depth, be well supplied with organic matter, not too acid or alkaline, and have an adequate supply of nutrients derived either from the soil itself, or from fertilizers and other outside sources as needed. Soils of any texture may be made into good agricultural soils but certainly the difficulties of developing a good soil are greatly increased at both extreme ends of the range of texture.

Virgin soils are seldom good agricultural soils, contrary to popular opinion. The reasons are obvious; if any one of the factors listed above, such as drainage, is not satisfactory the soil cannot be a good productive soil for most farm crops until the bad features have been rectified. Natural soils are found in all degrees of disorder when considered from the standpoint of what the agriculturalist considers order. In other words, God did not make soils specifically to comply with what man considers as the specifications of a good agricultural soil. God made all kinds of soils in all kinds of conditions, and man must modify them as necessary to meet his requirements. In many countries the majority of the soils can, for various reasons, never be made suitable for economic agricultural use; they may be too rocky, too mountainous, too cold, too dry, too wet, or too high in alkali salts. We shall now consider some typical natural soils and what must be done to make them into agricultural soils, where this is feasible.

The conversion of exposed subsoils and mine spoils into soils that are suitable for either forestry or cultivated crops is a rather special problem that is discussed in Chapter 26; similarly, peat and muck soils are considered in Chapters 29 and 30. The special problems involved in the development and use of soils in The Netherlands are adequately discussed by Meijers (1959) and will not be considered here.

CHERNOZEM SOILS

It is well to consider chernozem soils first, because they come the nearest to being good agricultural soils of any naturally occurring soils. Since they are formed in regions of low rainfall and mild climate, and under grass vegetation, they are commonly deep soils, high in organic matter and lime, have excellent structure, and are very high in plant nutrients. About the only factor that limits productivity is low rainfall. But it is this low rainfall that makes leaching unimportant, limits stratification in the profile, de-emphasizes drainage, and leaves an abundance of mineral nutrients in a highly available condition. The plant roots that may extend to depths of 4 or 5 ft., but are mostly confined to the surface foot, are the source of the abundant and deep supply of humus. This organic matter, and accompanying extensive biological activity, are in large part responsible for the excellent crumb structure. If all soils were chernozems, or chernozem-like, there would be little or no need for this present chapter.

FOREST SOILS

Forest soils may, for the purpose of this discussion, be divided into brown forest soils and those that are more typically podzolic. In general, the brown forest soils are those formed under predominantly deciduous vegetation and are either neutral or only slightly acid. The true podzols are formed under predominantly evergreen softwood vegetation and are often very acid.

Brown forest soils

Natural brown soils are commonly second only to chernozems in meeting the requirements of a good agricultural soil. Under conditions prevailing for centuries, or thousands of years, deciduous forests tend to build up a characteristic soil that is determined chiefly by the trees themselves and climate. The climax vegetation that becomes established leads to a climax soil that is also stabilized so long as conditions remain reasonably constant and man does not interfere.

The formation and nature of brown forest soils are discussed in Chapter 7, but need to be briefly considered here. The hardwood vegetation, occurring in a humid climate, has many taproots that extend down several feet into the subsoil, but most of the small feeder roots are usually in the surface one-foot layer. They absorb mineral nutrients which are transported to the tops and used chiefly for the production of leaves. At the end of each season, and to a lesser extent during the rest of the year, these leaves, together with twigs and limbs, fall to the forest floor and undergo decay. A mull layer forms that becomes a habitat for various kinds of woodland plants and animals, especially earthworms. This mull contains much of the calcium and other minerals that were in the leaves. It is worked over constantly by earthworms and other animals that eat it, or drag it into the soil where it is eaten later or undergoes decay. The result is a mixing of the humus with the upper foot or more of soil, leaving the mull layer rather thin and only slightly acid. Humus decreases with depth and blends gradually into the mineral soil below. Soil structure is usually good in the high organic layer of soil but the crumb structure may be less in evidence at lower levels.

Heavy rains leach out a portion of the bases in the mull layer and below, most of which are intercepted by the tree roots and returned to the surface again later with the annual leaf fall. Since the leachates are usually nearly neutral in reaction, they extract less mineral matter than where the percolating water is high in organic and nitric acids. This continuous cycling of nutrients accounts for stabilization of the soil with little tendency toward the distinct stratification and impoverishment that is characteristic of true podzols.

When man disturbs nature's equilibrium by removing the trees, then the natural cycle of elements is stopped. Leaching continues and bases are carried to the subsoil and water table, but now there are no tree roots to intercept this movement and return the minerals. Under humid conditions these brown forest soils may become poorer in plant nutrients and also in organic matter, since there is now no annual fall of leaves. Soil structure may also be affected unfavorably. This is the picture if the forests are merely removed and the soil left almost bare. Actually this is usually not the case because man substitutes a mixed agricultural system for forest vegetation. Plowing, cultivation, fertilization and proper cropping and livestock are now substituted for nature's method of soil maintenance, and under proper management there need be no decrease in fertility; there may even be an increase. The natural brown forest soil presents few unusual problems that are likely to lead to failure in this transformation from forests to arable land. Grasses and cultivated crops can now serve as organic matter sources instead of tree leaves, and fertilizers can replace any elements lost by leaching.

True podzols

A typical podzol is formed under a heavy layer of organic debris consisting chiefly of needles, cones, dead twigs and branches derived from the heavy stand of coniferous trees that may have been there for many years, usually centuries (see Chapter 7). These organic residues are low in bases, unsuitable as foods for earthworms, and are resistant to decay. The result is the accumulation of a duff or mor layer, often several inches thick. The natural cycle of removal and return of soil bases, so characteristic in brown forest soils, occurs to only a minor extent.

The heavy layer of peat-like debris that accumulates on the forest floor decomposes slowly to form organic acids that are periodically carried down the soil profile with each heavy rain. These acids extract most of the bases present. Iron and aluminum compounds, some clay, and other colloidal material including soluble organic matter move downward with the percolating water. The bases are largely lost to the ground waters, but the other substances are deposited in the subsoil in a zone below the bleached and extracted layer. The net result is an acid soil of low fertility with distinct A- and B-horizons, having very poor structure and marked stratification of organic matter. In short, it is usually not a good agricultural soil.

If the coniferous vegetation is removed from a typical podzol, and farm and garden crops planted immediately without any soil treatment, the result is likely to be disappointing. This is attributable to insufficient mineral nutrients, high acidity, poor soil tilth and aeration, and low organic matter of poor quality and poor distribution. Usually the podzol is not a soil of great depth, in contrast with the chernozem. This is due in large part to past climatic conditions; the podzol has been leached for centuries, whereas the chernozem has not been. The podzol can be made into a fairly satisfactory agricultural soil without great difficulty by following the procedures outlined throughout this book. In brief, these consist of plowing (the depth to vary with the soil), cultivation, liming, addition of fertilizers, and using any feasible methods of building up the organic matter. These may consist of adding animal manures, turning under crop residues, growing green manure crops and establishment of grass sods. Plowing and cultivation will of course help to mix the stratified organic matter, characteristic of the natural podzol, with the rest of the soil and break up any shallow hardpans. These farm practices require time, especially if a sod must be maintained for a few years, but eventually a good agricultural soil can be produced and with proper management will become increasingly productive. The newly-developed agricultural soil is likely in time to have properties that differ markedly from the original natural podzol, but its nature is such that only by constant attention to its needs will it continue to be a good agricultural soil. These needs center around the addition of adequate nutrients, the maintenance of adequate organic matter to insure good tilth, and providing proper drainage as necessary.

RED AND YELLOW TROPICAL SOILS

Red and yellow tropical soils (latosols) are generally recognized as among the most difficult of all widely-occurring natural soils to convert into agricultural soils that can be cropped satisfactorily year after year. Most of them are really problem soils that cannot be handled by the methods used in farming soils of cooler climates. Some of the problems and possible solutions are outlined below.

Soil characteristics

The red and yellow soils of the Tropics have often been described as lateritic soils, but strictly speaking, this terminology is incorrect. Sivarajasingham et al. (1962) define a laterite as a "highly weathered material (a) rich in secondary forms of iron, aluminum, or both; (b) poor in humus; (c) depleted of bases and combined silica; (d) with or without nondiagnostic substances such as quartz, limited amounts of weatherable primary minerals, or silicate clays; and (e) either hard or subject to hardening upon exposure to alternate wetting and drying." The so-called red lateritic soils have properties that agree closely with this definition, except that ordinarily they are not hard or subject to hardening on wetting and drying, but it has little to do with composition.

The chemical composition of 5 selected laterites (Sivarajasingham et al., 1962) is given here in Table 20.I. These data emphasize the extremely high content of the sesquioxides

TABLE 20.I

CHEMICAL COMPOSITION (%) OF SELECTED LATERITES (from SIVARAJASINGHAM et al., 1962; reproduced by permission of Academic Press)

Constituent	*Site*				
	1	*2*	*3*	*4*	*5*
Quartz	0.76	ND	ND	4.32	ND
Feldspar	ND	ND	ND	2.35	ND
SiO_2	1.77	0.37	1.93	17.08	31.37
Al_2O_3	4.32	43.83	62.32	20.83	19.22
Fe_2O_3	80.02	26.61	1.88	40.18	38.51
TiO_2	6.06	4.45	11.87	1.72	1.12
CaO	–	0.86	–	–	0.10
H_2O (loss on ignition)	7.06	23.88	21.54	11.05	9.10
	99.99	100.00	99.54	97.53	99.42

of iron and aluminum and the almost complete absence of bases and primary minerals. Centuries of weathering under conditions of high rainfall and a hot climate have resulted in the removal of nearly all of the nutrients that are required for plant growth.

The organic matter content of the lateritic-like tropical soils, especially the forested ones, is low primarily because of the high temperatures and rainfall, abundant plant and animal life in the soil, and the scarcity of inorganic colloids with which the organic matter might combine. Clays of the montmorillonite and illite types that are known to hold much humus are nearly absent from many of these soils. A considerable mat of organic matter does accumulate in time on the soil surface but no great portion of it accumulates in the mineral soil. It disappears quickly from the surface when the trees are removed.

Regardless of low organic matter, the red soils (latosols), that do not harden in the manner of the true laterite, usually have a fairly good structure and can be cultivated satisfactorily. It is indeed fortunate that the substitution of the sesquioxides of iron and aluminum for the clays and minerals that characterize soils in the Temperate Zone does not necessarily result in poor tilth. Organic matter is, for various reasons, very desirable in these as in other soils but is here less essential for good tilth than in nontropical soils. (The true laterites that harden into rock are of course of little use as agricultural soils.) Forest latosols are commonly low in exchange capacity with pH values of near neutral in the topsoil but more likely 4.5–5.5 at lower depths.

Natural vegetation

In their undisturbed natural state, tropical soils can support very large amounts of vegetation per unit area. This may seem strange considering the soil composition as shown in Table 20.I, and the very scanty amount of organic matter found as a thin layer on the surface. Moisture and heat are highly favorable for plant growth, and in the case of trees the increment of nutrients required annually is probably not as great as might be expected, since the trees may live for centuries. Their roots bring up nutrients from the subsoil and also intercept nutrients that are being carried down from the surface by rainwater. There is also circumstantial evidence, as stated in Chapter 10, that considerable fixation of atmospheric nitrogen occurs in the high-rainfall forest areas. Ruinen (1961, 1965) has presented scientific evidence in support of this view. If such fixation is of considerable magnitude and widespread, one of the main secrets of heavy tropical vegetation on poor soils is explained.

Greenland and Kowal (1960) determined the weight of vegetation on old secondary forests in the moist forest zone of Ghana and found it to be roughly 150 tons per acre dry weight. The amounts of the chief nutrients immobilized in the vegetation, expressed as lb. per acre, were: N, 1800; P, 120; K, 800; Ca, 2,400; and Mg, 350. The corresponding amounts of nutrients in the top foot of soil were: total N, 4,100; available P, 11; exchangeable K, 580; exchangeable Ca, 2,300; and exchangeable Mg, 330 lb. Of the total quantity of roots, 85.5% by weight were in the upper foot of soil. Nye and Greenland (1960) give much additional information on the weight and composition of the vegetation from forest fallows, and on the composition of the soils on which it grew.

Under forest fallow the rate of turnover of the nutrient elements is very rapid, according to Nye and Greenland (1960), and after a few years exceeds the rate of storage in the fallow. In addition to the nutrients in the litter fall, considerable phosphorus and potassium are leached from the green leaves, and the dead wood contains considerable calcium. About five tons per acre of dry litter falls on the soil annually, and most of it decomposes rapidly. The amount of nutrients added in the rain and as dust is very small in comparison with the amounts involved in natural cycling.

Many tropical soils are covered with heavy growths of grasses that may be as high as 12 ft. These moist savanna areas usually adjoin the tropical forests and may consist either entirely of grasses or of grasses with interspersed trees. In the drier regions the soil is likely to be covered with grasses that are only about 3 ft. high. The type and amount of vegetation are dependent upon the amount and time of rainfall, and on the length of the period when there is no rainfall.

Where the native tree vegetation is removed and the soil is cropped until it becomes unproductive, it is not uncommon for grasses, rather than trees, to become dominant. Such soils tend to deteriorate further because of annual burning, shallow grass root system, and the smaller mass of vegetation that holds the nutrients against leaching. Under tropical conditions trees are more effective in holding or restoring soil fertility than are grasses. The annual burning of grasses, and soil exhaustion, act as a severe handicap to the re-establishment of forests.

Native cultural methods

Shifting cultivation was primitive man's method of eking out an existence on many of the tropical areas, and that practice still prevails in many regions. What is meant by shifting cultivation? It varies from place to place but the principles involved are similar everywhere. Nye and Greenland (1960) describe a typical project. During the dry season the native cuts down the vines and trees except for a few trees that are greater than 2 ft. in diameter which he leaves to furnish a light shade. When dry, the cut vegetation is burned and the ash allowed to remain on the surface. When the rains begin "he plants maize with a digging stick into the rich layer of friable humic porous topsoil, which has been developed under the forest fallow. This is about 2 inches deep and consists on the immediate surface mainly of broken worm casts. He does not disturb the soil between the planting holes, since he weeds the young crop by slashing with a cutlass. During this period much of the surface of the soil lies bare to the tempestuous early rains, which shatter the crumbs and casts on the surface and may float away ash in the surface run-off. During the growth of the first crop, or shortly after it has been harvested, the farmer plants cassava and, as a rule, other long-growing starchy crops such as cocoyam, and plantain. Small patches of land may be reserved for peppers, okras, spinach plants and other vegetable crops usually managed by the women. The crops grow well ahead of the weeds, and by the end of the rainy season the land is well covered with vegetation. During the next year the plantains and some of the cassava and cocoyam will be harvested, while the remainder are left to grow further into a third or fourth year to be harvested as needed, or abandoned to the regrowth of forest. Thus after the first year the land has always a cover of vegetation. The developing 'bush' springs from the stumps and large roots left after clearing the previous fallow, and from germination of seeds already lying in the soil or carried in from adjoining areas of forest. The dense mass of the developing secondary forest is soon dominated by light-loving species. . . Regrowth is rapid and the secondary forest may well be 20 feet high after five years and 50 feet after ten. If it is allowed to continue growing for twenty years the early dominants are replaced by the variety of slower-growing species found in the mature forest. Eventually an old secondary forest scarcely distinguishable from the original is developed."

The kinds and numbers of crops grown on a cleared area vary widely in different countries, but commonly as many as a half dozen are grown at the same time in a nonsystematic arrangement. Sometimes these crops are planted on unburned cleared areas, but burning of the debris is a more common practice. Usually the cleared area is allowed to return to bush after two or three years chiefly because of declining fertility, but also because of the invasion of the natural vegetation. Nye and Greenland state that under African conditions shifting cultivation can normally support a population of less than 20 per sq. mile. The system is incapable of supporting dense populations.

Another type of shifting cultivation is that involving primarily grasses rather than trees. In the regions of high rainfall, where the grasses may be as high as 12 ft., the grass is usually burned annually. The soil is then left nearly bare during most of the dry season, except perhaps for a few fire-resisting trees. In order to get rid of the grass roots the soil is often scraped into mounds about 2 ft. high the first year and planted to various crops. A variety of crops is then grown on the soil for a period of about three years, after which the land is abandoned to native grasses and other plants. After ten or more years the cycle can be repeated. In the drier regions the savanna consists chiefly of short grasses, and because of less moisture and longer dry periods the crops grown must be of the short-season type.

Shifting cultivation may involve only the matter of shifting crop production from one field to another, or in some cases a tribe may for various reasons move from one locality to another. In either case the effects on soil fertility and crop production are much the same, since on any one piece of land there is the long fallow period followed by the short cropping period. Occasionally the fallow system is avoided by individual farmers, or by those in a village, if livestock are kept in appreciable numbers. In this case the animals may graze over a considerable area, and the manure be used to fertilize a comparatively small area annually devoted to crops. Soil fertility is thus maintained on a small area at the expense of many acres used for grazing.

Why the fallow system?

According to Nye and Greenland "the first sight of native subsistence farming in the semi-deciduous forest region, e.g., in Ghana, presents an appearance of bewildering confusion to any one familiar only with the pattern of well ordered fields under single crops characteristic of more advanced systems of farming. There are no clear boundaries, individual fields can scarely be discerned, and while some patches are definitely under crops, and others are under thick regrowth of forest, there is a middle group in which perennial crops survive amidst a regrowth of forest which is gradually choking them. Some patches of land carry only one kind of crop, yet others appear to carry a mixture of up to a half-a-dozen kinds in a seemingly haphazard arrangement."

The primary reason for this fallow system of farming is low soil fertility. Many attempts have been made to substitute European methods for this primitive system but frequently with little success, mostly because in many soils essentially all of the mineral nutrients required by plants are absent and usually cannot be supplied economically or satisfactorily as fertilizers. The fertilizer materials are seldom available where needed, are expensive, and if used are either fixed by the iron and aluminum present or are leached from the soils of these regions of high rainfall. Soil and climatic conditions, and cropping systems, vary so widely in the Tropics that broad generalizations are inadvisable. Actually, many fertilizer trials (see Nye and Greenland) have given good results on some forest and savanna soils, which furnish much hope for the future.

Clearing the land of trees and grasses presents problems for those not equipped with modern machinery, but this will no longer be a problem if continuous culture should become feasible. Still another severe handicap in crop production in many areas is either inadequate rainfall, very long drought periods, or great uncertainty as to when the rains will come.

In the face of all of these handicaps it is not surprising that the shifting system of cultivation has prevailed over the centuries. Under this system, trees with deep roots can assimilate nutrients in the subsoil and being carried down in the leachates. When the leaves and twigs fall, some of these nutrients are returned to the soil surface. When the trees are cut down the organic matter on the soil surface decomposes rapidly but the release of nutrients continues long enough for two or three crops. The ashes serve as a further source of nutrients. Both sources are soon gone and the 10- to 20-year fallow period is required to restore the fertility to somewhere near its previous state. Toxicity in the soil is often a factor, but trees and grasses can tolerate these toxins, whereas cultivated crops cannot when most of the organic layer is oxidized.

During the fallow period nutrients accumulate both in the vegetation, and in the topsoil in the form of humus. These capital gains represent the main benefit from the fallow, but improved physical conditions in the topsoil, and increased availability of the nutrients, are also important. Other benefits may include reduction in pests, diseases and weeds. The increase in organic nitrogen in the topsoil is especially important since nitrogen in the vegetation is lost when it is burned. Nye and Greenland estimate that this increase of nitrogen in the topsoil under forest fallow is about 35 lb. per acre annually; under savanna it is probably about 10 lb.

Improved soils and cultural systems

The development of good agricultural soils suitable for the yearly growth of a wide variety of vegetable and field crops, starting with the typical lateritic-type tropical soil, is very difficult. The reasons, already given, revolve around deficient minerals, climatic problems, rapid disappearance of organic matter and the difficulty in using fertilizers satisfactorily and economically (Ignatieff and Lemos, 1963; Kellogg, 1963). Present indications are that man must be content with the use of many of these soils for special purposes to fit local conditions. Shifting cultivation will doubtless continue in many places but certainly to a lesser extent in the future than in the past.

Some tropical soils are now being used for the production of abundant crops, and this tendency will certainly increase with time, and with the expansion of populations. Most success to date has been associated with the growth of tree and other perennial crops. These include rubber, bananas, cocoa, coffee, abaca, and the oil palm. Tree crops not only minimize soil exposure and hardening, but the roots assimilate nutrients in the subsoil just as do the trees in the virgin forests. In the moist tropics paddy rice culture is also an excellent possibility where a water supply is available and can be utilized economically for this purpose. Rice can be grown without fallow periods, soil erosion, or appreciable soil exhaustion. Future research, which is much needed, should find further ways of utilizing these comparatively infertile soils. In such studies high priority should be given to the development of fertilizers that are especially suited to tropical conditions. Many, but not all, of these soils are phosphate fixers but it should be possible to develop materials and methods that will largely avoid such fixation. Leaching of all nutrients in regions of high rainfall is also a major problem that needs special attention. Organic matter maintenance, which is a major consideration in soils of the Temperate Zone, is of less importance in the Tropics where dense soil structure (other than in lateritic materials) is usually not a major problem. Organic matter in the form of animal manures and compost should, nevertheless, be used to the fullest extent to serve as nutrient sources even if not needed for soil tilth.

In their discussion of the future prospects for the red and yellow tropical soils, Nye and Greenland state that "eventually the demand for food and livestock products by the growing towns, and availability of cheaper fertilizers, may bring to the forest regions continuous cropping maintained by large applications of fertilizer, and pastures grazed by much improved animals, but at present these lie well into the future. Possibly in an ideally planned economy the forest lands would be left to produce timber or the perennial cash crops like cocoa and rubber for which they are so well suited, and would import their subsistence requirements from the savanna regions or even further afield. However, in so far as subsistence crops continue to be grown on upland forest soils some form of rotation involving natural or planted fallows seems likely to persist in the forest regions for very many years."

Nye and Greenland state further that "there is however no evidence yet that a planted fallow will restore the fertility of a forest soil any faster than the natural woody fallow. It is the fastest growing species in the natural fallow that win the race for light, and the possibilities of finding very much more vigorous species are not hopeful. In particular we must emphasize that the nitrogen status maintained beneath a forest fallow is good, and there is no reason to think that long-term leguminous fallows would offer any advantage. Short-term leguminous fallows or green manures have the disadvantage of leaving the soil exposed while they are being established." The planting of fallows that can be put to use, such as valuable trees or bananas, has been practiced, but only to a limited extent.

One of the main difficulties of producing a good agricultural soil in the savanna regions is, as stated above, lack of moisture and long dry periods. Where moisture is adequate these areas can likely be used to a greater extent in the future for larger numbers of livestock using a ley system of farming. Fertilizers that supply both nitrogen and phosphorus will be essential, and all manure should be fully utilized. By keeping the soil in crops practically all of the time erosion will of course be kept to a minimum.

POORLY DRAINED SOILS

In the process of conversion of a poorly-drained soil into a good agricultural soil the first and most important step is obviously to get rid of the excess water by suitable surface or subsurface drainage systems. This is often not easy, especially when dealing with fine-textured soils that in humid regions usually have become so puddled that the rate of water movement through the soil is extremely slow. On many farms there are low areas, usually of fine-textured soils, where water tends to accumulate and where drainage is inadequate even though other portions of the field are well-drained. Frequently the farmer will plow, plant and cultivate through these wet places rather than delay farm operations until these areas are sufficiently dry. This causes puddling and such bad structure that the soils are not suitable for general crop production even when they dry out. Livestock that are allowed to graze on saturated soils can produce the same effect.

After adequate drainage has been provided much effort and time may still be needed to convert the soil into one suitable for general cropping. The establishment of good structure, good aeration, and an adequate rate of water movement in a tenacious puddled clay requires special ingenuity in the use of all of the standard soil management practices. Replenishment of organic matter under humid conditions is one of the most important essentials. This does not necessarily mean applying outside sources of organic matter, such as crop residues and animal manures, although these are certainly beneficial. A more practical method is usually to grow initial crops, usually grasses, that have masses of fine roots that will rather quickly establish a satisfactory structure at least in the surface few inches. After perhaps three or more years the sod can be turned under, if desired, and one or more crops of corn grown. A deep-rooted legume in the rotation will also help materially in opening up the dense, previously impervious, subsoil. Eventually a soil of good structure to a depth of at least 6–12 inches should be established and with improved structure the ease of drainage will increase.

Good farm management necessarily includes the addition of lime if needed; fertilizer nutrients; and the control of insects, diseases and weeds. Soil and climatic conditions vary so widely from place to place that there can be no one standard system of making good soils out of bad ones, but the principles involved are much the same everywhere. There are few places in agriculture where organic matter is more essential than in this area of structure improvement, starting with a soil that has been waterlogged for many years. Perhaps it is not, strictly speaking, organic matter itself but the biological, physical and chemical effects that are produced by, or associated with, the growth of a finely divided root system of a vigorously growing plant.

Since wet areas and low-lying soils tend to be fine textured, it follows that once these soils are gotten into good physical condition they are likely to be very productive. They will not be suitable for all crops, of course, but this is true of all soils. Good farm management includes the selection of the crops and rotations that best suit the soil and climate. On many farms there may be poorly-drained soils that economically cannot be adequately drained for a variety of crops. Often these can be utilized for special crops, such as cranberries, rice, or perhaps even for hay crops.

SALINE AND ALKALI SOILS

Soils that have been harmed by soluble salts are designated as saline or alkali soils. Saline soils contain excess soluble salts only, whereas alkali soils are high in adsorbed sodium. The chief soluble salts are the chlorides and sulfates of calcium and magnesium; either carbonates or bicarbonates and sometimes boron may be present. Extensive leaching with comparatively salt-free water may remove nearly all of the soluble salts from soils and make them suitable for crops, but sodium is held on the exchange complex, and this makes alkali soils very difficult to handle.

The presence of excess salts occurs in regions of high temperatures where the rainfall or irrigation water is inadequate to remove the soluble salts. Salt accumulation may also occur where the drainage is poor, where the ground-water table is high, where there is a seepage from higher levels, and where the irrigation waters are high in salts. The salts tend to accumulate at the soil surface as a result of upward movement of the water caused by evaporation and transpiration. The higher the water-table the greater is the movement of salts to the surface. When soils are first put under irrigation there is often a tendency for the additional water to raise the water-table unless the drainage is adequate to remove the additional water. Often the salt concentration in the irrigation waters is comparatively high, and if so, this greatly increases the problem of salt control.

Plant growth is retarded or injured by soluble salts because these salts interfere with the uptake of water, and the effect is largely independent of the kinds of soluble salts present. Retardation of growth increases directly with salt concentration. Sometimes elements, such as boron, may be present in solution and produce a direct toxic effect other than the usual soluble salt effect.

In alkali soils it is the sodium adsorbed on the exchange complex that produces the injury to plants. This injury may be the result of direct toxicity, high pH, deflocculation of soil aggregates, and a disturbed salt balance that results from the substitution of the sodium for much of the calcium and magnesium that are usually the dominant bases in normal fertile soils. Improvement of alkali soils involves chiefly the replacement of much of the sodium by calcium or magnesium, followed by other practices that produce a good soil structure.

Saline soils that are not high in sodium are usually well flocculated as long as the dissolved salts are present. Even alkali soils usually remain flocculated if they contain considerable soluble salts, but if these are removed the deflocculating effect of sodium manifests itself rather quickly and the rate of movement of water through the soil is soon greatly reduced.

The conversion of a saline soil into a good agricultural soil consists, obviously, in the removal of excess salts to the point where retarded uptake of water by plants is not a serious problem. This is not always easy because irrigation water is itself a source of salts, and also because of costly engineering problems that often prevail, but which need not be considered here. The difficulties can often be minimized by the selection of salt-tolerant crops. Since saline soils normally have good structure (assuming that no hardpan is present) and are usually deep, they are commonly not problem soils once the soluble salt level can be controlled adequately. Good soil management will, however, provide for a suitable cropping system, adequate nutrients, a good organic matter supply and proper tillage practices. Organic matter is usually less essential for good tilth in these soils than in many humid soils. It is nevertheless essential as a constant source of energy for microorganisms and the continual release of available nutrients. In these soils that are normally hot there is no possibility of, or need for, building up a high level of humus. An active, constantly replenished, source of organic matter is very desirable and assures a continued productive soil; it acts as a conditioner and buffer.

The development of a good agricultural soil from an alkali soil consists in establishing adequate drainage and in the addition of soluble calcium and magnesium in such amounts, by methods that will assure that these added elements will replace much of the sodium adsorbed on the exchange complex. The kind of substance added varies with the soil, cost, and local conditions. Among those used are calcium chloride, calcium sulfate, calcium carbonate, aluminum sulfate, iron sulfate, sulfur and sulfuric acid.

After a satisfactory sodium to calcium plus magnesium ratio has been established and drainage is satisfactory, there remains the major problem of establishing a good soil structure in the profile. This can be done, as elsewhere, by the growing of crops with fine and deep roots, by providing for as much soil organic matter as possible and by use of suitable systems of plowing and tillage at times when puddling can be avoided. If for any reason, e.g., cost, it is not possible to keep the level of sodium or soluble salts low, then an agricultural soil suitable for a wide variety of crops cannot be attained. It must then be used, if at all, for special salt-tolerant crops.

COARSE-TEXTURED SOILS

Very coarse-textured soils are normally infertile and non-productive because of their very low content of both inorganic and organic colloidal materials; their lack of essential plant nutrients; and their low water-holding capacity. Many of these soils are so marginal that they can best be allowed to return to forests. At least it is usually unwise to try to convert most of them into agricultural soils for a wide variety of crops. If the sand is underlain by clay at a depth of perhaps 1–3 ft., then the water relations are such that the soil can usually be utilized for the growth of many kinds of crops, but facilities for irrigation may be needed. If so utilized, it may be necessary to fertilize two to four times per year, depending on the crop, soil and climate, rather than only once or twice as is common for field crops growing on loamy soils. As the texture becomes finer, and the percentage of SiO_2 less, the difficulty of using soils for general cropping decreases markedly.

Very sandy soils can often be used very profitably for the production of speciality crops such as quick-growing vegetables, melons, small fruits and tree fruits. These crops will need to be supplied with adequate commercial fertilizer as needed. Fruit trees and bush fruits may possibly be grown in humid climates without irrigation, since they send their roots to depths of 5–10 ft. or even more if the subsoil is such as to permit this. Short-season vegetables, if grown in the cooler seasons, may also obtain enough moisture from the normal rainfall, but irrigation is likely to be necessary in certain years.

Organic matter can play an important role in the use of very sandy soils, regardless of the use that is made of these soils. Often the organic colloid in these soils constitutes half or more of the total colloid, and much more than half of the exchange capacity since its exchange capacity may be 10–20 times as great as that of clay. It is obvious, therefore, that a special effort should be made to supply the soil regularly with as much animal manure or crop residues as is economically feasible. One cannot build up organic matter appreciably in these soils, because conditions are ideal for rapid biological oxidation of added carbon sources. Constant additions of organic matter do, nevertheless, serve a good purpose even if decomposition products disappear rapidly. While there, organic matter adds to the deficient exchange complex and releases available nutrients as decay proceeds. These released nutrients include the minor elements that are so important in a soil that consists almost entirely of SiO_2

There is considerable doubt as to the advisability of growing crops for use as green manures on very coarse-textured soils. These crops are not needed for structural improvement, as on heavy soils, but they are needed as sources of active organic matter. Under some conditions deep-rooted legumes, such as kudzu, alfalfa, sweet clover, crotalaria and pigeon pea may be grown, possibly without irrigation, and be added to the soil directly, or indirectly as animal manure. Whether this would be profitable or not is dependent upon local conditions, such as abundance of land and water, and cost of labor. Usually it would be more practical to utilize quick-growing non-leguminous catch crops or winter cover crops that assimilate nutrients that would otherwise be lost, and which may be grown without the use of much, if any, irrigation water.

SOIL FORMATION FROM WASTE ASH

One of the by-products of industrialization is large quantities of waste ash that remain when low-quality coals are burned for the production of electricity. It has been stated that in England and Wales during the 10-year period prior to 1961 about 25 million tons

TABLE 20.II

COMPARATIVE PROPERTIES OF FERTILE AND ASH SOILS (from COPE, 1962)

Property	*Fertile soil*	*Ash soil*
Aggregate stability	good	poor
Water infiltration	good	restricted by capped surface
Water percolation	promoted by vertical structure	restricted by horizontal structure and compacted layers
Wind erosion	not subject to, in U. K.	subject to
Water erosion	resistant	susceptible
Available water	3 inches (8 cm) water available in root range of most crops	available water similar except where salt concentration occurs
Nutrient content	well balanced supply of all nutrients	very deficient in N, high in K and P, but P unavailable. Micro-nutrients adequate
Nutrient retention	good for cations, whilst some anions are held by microflora	poor for both cations and anions. Microflora not sufficient to hold anions
pH	6.0–7.0	8.0–11.5
Soluble salts and electrical conductivity	not too high (electrical conductivity of saturation extract < 4 mmho/cm	salts low to very high (electrical conductivity of saturation extract 2–13 mmho/cm)

of ash were dumped on land to an average depth of 15 ft. (4.5 m), covering over 1000 acres (400 ha). Cope (1962) has considered the possibility of converting this waste material into a "soil" that will serve as a satisfactory medium for plant growth. The usual method has been to cover the wastes with a thick layer of topsoil but topsoil is seldom available in sufficient amounts.

Table 20.II, taken from Cope, shows how an ash soil differs from a hypothetical fertile soil. It is light brownish-grey to dark purplish-grey and consists of more than 50% glassy material, mostly 20–200 μ in diameter mixed with larger particles of ash and clinker. Ash soils have very poor crumb structure and low exchange capacity, as would be expected, since organic matter is absent.

Ash soil is very low in nitrogen and non-retentive of added ammonium and nitrate salts. It is usually well supplied with calcium, potassium and minor elements. Under the high pH (8.0+) conditions most of the phosphorus present or added at low rates is fixed by aluminum.

Initially, ash soils are high in soluble salts but these are leached out fairly readily. Boron is likely to be present in toxic amounts and persists for many years as it is gradually released from glassy particles. Cope reported that plants grown on ash are likely to be high in molybdenum, copper, and sulfate, although these are not present in toxic amounts. Ash is sterile at first but high microbial populations are readily attained after inoculation and provision of an energy source.

In summary of his studies on the reclamation of ash soils, Cope states that "the adverse physical structure and also to some extent the low nutrient retention can be improved by application of 2 to 3 in. (5 to 8 cm) of any clayey material. This need not be good quality topsoil, since subsoils, or even unburnt shales, have proved effective. Pozzolanic cementation in ash profiles can be broken up by subsoil cultivations, thus promoting percolation and leaching of toxins. Time and natural weathering will reduce soluble salts and particularly the toxic amounts of boron in ash, while much can be achieved by the selection of boron-tolerant crops. Some crops, for example white sweet clover, are especially effective, since, when inoculated with *Rhizobium*, they enrich the ash soil with nitrogen. In addition, the tops contain much boron and molybdenum which can be carted off the site. Heavy dressings of phosphates can overcome fixation by aluminum, and the use of frequent small dressings of nitrogen fertilizer improves nitrogen utilization by the crop. Excellent crops of some tolerant plants have been grown directly in ash soil, and with comparatively shallow applications of soil the range can be extended considerably." Where organic matter in the form of sewage compost was added, aggregation was increased markedly.

This discussion of comparatively unimportant ash soils emphasizes that much can be accomplished with very uninviting soil materials if toxicity can be overcome and organic matter plus nutrients as needed are supplied.

AGRICULTURALLY EXHAUSTED SOILS

Soils of the humid region and Temperate Zone that were at one time productive often become comparatively nonproductive after several years of cropping if little attention is given to maintenance of soil fertility. Among the chief reasons for the decrease in yields are: decrease in available nutrients; increase in acidity; lack of adequate organic matter; poor physical condition; build up of toxic substances; plant diseases; insects; and weed competition. There are other possibilities, some of which are closely related to the above, namely inadequate aeration, hardpans, slow infiltration, and poor drainage.

The extent to which soil fertility decreased in Europe during the Middle Ages when the land was managed under a communal system of farming is pointed out in Chapter 1. As this system was displaced by private ownership of enclosed small acreages, and a ley system of farming with increased livestock was adopted rather generally, the long decline of fertility was halted. A variety of crops was then grown and, under private ownership, more effort was exerted to increase productivity.

Rapid progress came with the Industrial Age when more capital was made available for land improvement, including drainage, liming, farm machinery, etc. When commercial fertilizers became available in the latter part of the 19th century, crop yields really began to take a big leap forward and the curve is still upward.

In the comparatively recently settled regions of North and South America and Australia, soil deterioration has frequently proceeded at a much more rapid rate than took place in Europe. With fertile, cheap land abundant, and the population comparatively small, there was little incentive to be concerned with loss of fertility. The profit motive prevailed, as usual, and farmers followed practices that gave them the greatest return for the least labor and capital. Losses through erosion were tremendous, but fortunately in the United States, through the efforts of the U.S. Department of Agriculture, the public began in the early part of the present century to be made conscious of the need for conserving soil fertility. Vast strides have been made in recent years, but there is still plenty of room for progress.

The steps that need to be taken in order to make good agricultural soils out of exhausted ones need not be discussed in detail here; they are obvious from the discussions throughout this book. Since these soils were at one time reasonably productive they are usually not problem soils. The need is to correct the bad conditions, such as acidity or toxicity, apply nutrients as needed, and adopt a cropping system that will provide for an adequate level of organic matter and possibly some nitrogen gains from the air via legumes. A supply of animal manure is highly desirable but not essential; many cropping systems have been shown to supply as much organic material in the form of roots and other residues as is necessary to give the run-down soil good heart, as the British say. The multitude of insecticides, fungicides, and herbicides, now available in the market, should eliminate most of the insect, disease, and weed problems. With the knowledge that is now available, a greatly exhausted soil that at one time grew good crops, can with proper management usually be brought back into profitable crop production in a matter of 10 years or less. The chief exception would be the soil that has been so badly eroded that only little more than gullies and bare rock remain. Many soils in the eastern United States that were abandoned in the early period of colonization are now producing bumper crops yearly. Even soils that were at one time considered too marginal for anything other than grass and trees have also been brought into profitable production.

A permanent agriculture at a high level of production has at last been arrived at without the use of human manures and other wastes, stressed so much by King (1911) in his writings on China and Japan, and by those who are commonly classed as organic gardeners. Of course this permanent agriculture is dependent upon adequate supplies of N, P, K, Ca, Mg, and trace elements. Nitrogen, which is the most important of these, is available commercially from the air in unlimited quantities. There is also no lack of Ca, Mg, and minor elements, and the supply of P and K is adequate for at least a few centuries. Tremendous quantities of the five major elements are removed each year in the bumper crops now being harvested, and leaching also removes large amounts of all of these except P. Nevertheless, with our present knowledge there need be no decreases in yields in the foreseeable future. It would be fine if satisfactory methods could be found for salvaging the large amounts of nutrients that are now lost to the rivers and oceans, and probably this will be done in time to a greater extent than at present. In the meantime we must continue to rely on mining operations to supply all of these, except nitrogen, that are not supplied by the soil.

In closing this chapter I wish to call attention to the urgent need for protection and preservation of our agricultural soils for use in food production. Many of the most productive and best-located soils are now being removed from agriculture and being utilized for industry, housing developments, road construction and new cities. This urban sprawl has been happening at an accelerated rate, and at a time when the need for more food for more people has been all too evident. Good agricultural land is comparatively scarce, and much more effort should be made to see that it is protected. If this were done, much of the new construction could be shunted to hilly and marginal land that is of little use for crop production. This is primarily a task for federal and state governments but education of the public might also help to achieve the desired goal (see Gaffney, 1958).

REFERENCES

Cope, F., 1962. *Trans. J. Meet. Comm. IV, V, Int. Soc. Soil Sci., N.Z.*, pp. 859–863.

Gaffney, M.M., 1958. In: *Land-Yearbook of Agriculture.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., pp. 503–522.

Greenland, D.J. and Kowal, J.M.L., 1960. *Plant Soil*, 12: 154–174.

Ignatieff, V. and Lemos, P., 1963. *Soil Sci.*, 95: 243–249.

Kellogg, C.E., 1963. *Soil Sci.*, 95: 221–230.

King, F.H., 1911. *Farmers of Forty Centuries.* Democrat, Madison, Wisc., 438 pp.

Meijers, F.G., 1959. *Adv. Agron.*, 11: 333–368.

Nyhe, P.H. and Greenland, D.J., 1960. *Commonwealth Bur. Soil Sci. (G.B.), Tech. Commun.*, 51: 1–156.

Ruinen, J., 1961. *Plant Soil*, 15: 81–109.

Ruinen, J., 1965. *Plant Soil*, 22: 375–392.

Sivarajasingham, S., Alexander, L.T., Cady, J.G. and Cline, M.G., 1962. *Adv. Agron.*, 14: 1–60.

Chapter 21

MAINTENANCE OF SOIL ORGANIC MATTER

INTRODUCTION

In the various chapters of this book the functions and importance of humus in soil are considered in considerable detail. Although good crop yields can be obtained in sand and water cultures to which no organic matter has been added, this cannot be done without very careful attention to nutrient levels, solution concentration, pH, and other details. In very heavy soils that tend to compact easily, poor aeration and difficulty of root penetration are also likely to be encountered at very low levels of humus. Adequate soil organic matter greatly reduces the difficulties of good crop production. Agriculturalists realize the major benefits of soil organic matter and find it profitable to go to considerable effort and expense to insure that their soils are kept well supplied with the substances from which humus is derived (Bradfield, 1954). This maintenance of an adequate supply of organic matter is of primary importance in productive agriculture. Just what level of humus should be maintained depends on many factors that are considered below.

THE HUMIFICATION PROCESS

The humification process is a dynamic one because it is brought about by living organisms that are always active so long as active forms of organic matter are present. Whatever the form of organic matter added, it is subject to attack by the microflora and fauna that depend upon these substances for their energy supply and for the ingredients necessary for the production of their progeny. And as one generation dies, another follows that lives in part on the remains of the previous one. But since as much as, or more than, 90% of the readily available energy may be utilized within a few weeks, it is obvious that in the absence of new sources of organic materials the system would rapidly run down; that is, go from a highly-dynamic to a near-static one. In this case the residual materials would continue to decompose slowly and the humic materials, even if they became completely inert, would still be beneficial although inadequate.

Present evidence (Bartholomew, 1965) indicates that nearly all organic matter in soils, other than that added during the past two or three years, consists of the residues of microorganisms. Certainly all, or nearly all, of the plant protein and other nitrogenous constituents are utilized rather rapidly by microorganisms and converted into microbial protein. Most of the carbon compounds are oxidized to carbon dioxide and water but a small proportion is built into the cells of microorganisms. Almost the only plant carbon that remains unassimilated by microorganisms is the carbon in lignin and its degradation products, and even these substances are slowly attacked. Rather extensive researches, such as that of Gottlieb and Hendricks (1946), have demonstrated that the lignin-like material in soil humified matter is not true lignin. It is lignin that has been markedly changed chemically, as by the elimination of methoxyl groups. The breakdown products are known to combine with amino acids to form large molecules that we commonly designate as humic substances or humus. These substances are therefore not almost wholly the residues of plant substances as was at one time thought, but rather primarily the products of microorganisms that may have undergone synthesis, degradation, and polymerization (see Chapter 8).

There is usually a marked similarity in the composition and properties of humic substances formed from different kinds of plant material, provided that they were formed under similar conditions with respect to temperature, moisture, aeration, pH and other factors that affect microbial growth. This is not surprising in the light of our present knowledge that the humic constituents must in large part pass through microorganisms on their way to becoming humus. A marked deficiency in nitrogen in the original plant materials may affect somewhat the properties of the humus that forms, but even in this case the effect may be more on the rate of formation, and on the amount of humus formed, than on its chemical or physical nature. A marked change in environmental conditions such as submergence, or a marked difference in pH, will affect the nature of the humic substances formed, as would be expected, since such variations affect the composition of the microflora, rate of decay, completeness of decomposition, and probably some phases of polymerization. In our better cultivated soils humus composition tends to be surprisingly constant.

ACTIVE VS MORE RESISTANT ORGANIC MATTER

Active organic matter may be defined as organic matter that contains a considerable amount of plant materials still undergoing active decomposition in the process of being converted into microbial material and humic substances. If no new sources of organic matter have been added recently, then the organic matter consists largely of humic substances and is comparatively inactive biologically. There is, of course, no sharp line of demarcation between the two; the active form is constantly changing to the less active form, but even the more resistant forms of soil organic matter are usually able to support considerable microbial life.

Bartholomew (1966) states that "there is no reason to believe that any plant material or constituent therefrom is completely immune to biological decay. If such were so the earth's surface would long ago have accumulated very large quantities of organic substance. All organic debris is susceptible in some measure to microbial decomposition." The biologically stable product formed is the material that we commonly designate as humus. In his discussion of this material, Bartholomew states that "the most widely accepted hypotheses regarding humus consider it to be a semi-symmetrical product chemically. The theories of formation and constitution appear to require the coupling or reaction, in specific ways, of certain reactive groups on the primary building products. Such reactions of necessity would result in quasi uniformity in microchemical constitution." (See Chapter 8.)

During the first third of the present century much emphasis was placed on the necessity for the maintenance of a highly active form of organic matter in our soils. In more recent years the emphasis has gradually shifted more to the need for the maintenance of adequate soil organic matter without special emphasis on active organic matter. There are exceptions to this general statement, as where crop residues are used in soil conservation, compost in gardening, and organic residues for improvement of soil aggregation and structure.

The decreased emphasis on active organic matter may be attributed primarily to the increased use of commercial fertilizers. So long as organic matter was the chief, and often the only, source of plant nutrients other than soil, it was very essential that all organic residues be incorporated into the soil, and that they decompose readily and release their mineral nutrients. Over the centuries organic matter was highly prized chiefly because it was the source of plant nutrients. As knowledge of soil microbiology developed, the role that active organic matter played in serving as an energy source for the microbial population was often stressed, but this was only another aspect of the problem of getting adequate nutrients for crops. The microorganisms, considered by many as so essential, were merely the agents for releasing nutrients from decaying organic matter; they could release only minimal amounts from resistant soil organic matter that furnished them little energy.

With the advent of abundant supplies of commercial fertilizers at reasonable prices the need for organic matter, especially for active soil organic matter, was lessened. This shift in emphasis came about gradually and almost unnoticed. Organic matter was still important but more as a factor in soil aggregation and tilth, in exchange capacity, as a buffer, as a source of minor nutrients, for erosion control, and for water infiltration and water use efficiency. Many of these benefits are realized more from well-humified organic matter than from active organic matter. We can of course maintain a good supply of humus under normal farming conditions only by the addition of undecomposed crop residues that are the source of the humus.

The emphasis on organic matter as a nutrient source has, as stated above, been followed by increased emphasis on its importance in the maintenance of good soil tilth. But changes in our concepts are occurring even in this latter phase of the subject. This is brought out very clearly in Chapter 16. Many publications, e.g., Stallings (1953), have emphasized the need for this continuous return of crop residues to soil in order to insure the maintenance of good aggregation. It has long been surprising to the author that such extreme emphasis should have been placed on the necessity for such frequent additions in order to maintain aggregation, in view of the often-demonstrated fact that most of the aggregates so formed are non-stable and break down rapidly. Organic matter plays a very important role in soil aggregation and tilth but not quite in the manner that many have supposed (see Chapter 16). Polysaccharides, synthesized by microorganisms, and humus decomposition products may stabilize aggregates formed by physical forces, but these materials alone have negligible ability to form stable aggregates.

HUMUS SOURCES AND THEIR USE

The characteristics and merits of organic materials that are commonly used as humus sources in agriculture are discussed below. These include crop residues that never leave the soil, portions of plants that are removed and returned, outside carbon sources, and crops that are incorporated into soil for soil improvement. These humus sources are not of equal value per unit of carbon, and maximum benefits are realized only by varying the methods of use to fit the individual soil and cropping system. These benefits may include not only the maintenance or build-up of soil organic matter but also better tilth, increased water use efficiency, improved nutrient status of the soil, increased buffer and exchange capacity, and erosion control.

Crop residues left on the soil

All crops add carbon to a soil in the form of root residues even though essentially all of the above-ground portions may be removed. This added carbon may constitute as little as about 5% of the total crop carbon in the case of some vegetable crops, and as much as perhaps 40% in some of the deep-rooted perennial crops. The above-ground carbon that is returned to the soil may be near zero for many crops and perhaps 50 to near 100% for others, depending on the kind of crop and the disposition made of it.

According to data reported by Hardy (1944), a typical sugar-cane crop produced about 3,500 lb. of roots per acre in the upper 6-inch layer of soil. The cane trash had a weight of about 20,000 lb. Of course these values are greatly in excess of those for most crops grown in more northern regions.

In the humid region most crop residues are incorporated into the soil by plowing or discing at the time most convenient for the plowing operation. Where the mass of residue is large and the texture coarse, as in the case of cornstalks, it is a common practice to cut up the material and perhaps disc it into the soil several weeks prior to plowing. This facilitates the plowing operation and also provides considerable protection of the soil against erosion. Unless some method is used for the breaking up or pulverizing of cornstalks and similar coarse materials, they may interfere with later farming operations if a cultivated crop follows.

Mannering and Meyer (1961) conducted simulated rainfall experiments on two loam soils from which they concluded that soil losses can be reduced significantly if cornstalks are shredded in the fall rather than allowed to remain as left by a cornpicker. Discing of shredded cornstalks increased soil losses.

On a large percentage of the farming areas the above-ground portion of the crop is used in its entirety for silage, for dry feed, or for other purposes. If the roots constitute the only new carbon source for humus maintenance few problems exist, but where large amounts of both tops and roots are present the carbon–nitrogen ratio may be sufficiently wide to cause nitrogen deficiencies when decay begins to proceed rapidly during the spring and summer months.

In the semi-arid regions the tendency is more and more to leave the residues on the surface to serve as a trash mulch. This practice, which is referred to in Chapter 25, favors water infiltration and erosion control, but presents problems in connection with cultivation and sometimes with weed control. The rate of decomposition of the organic residues is less when left on the surface than when plowed under, but their contribution to humus maintenance is not appreciably different.

Where the climatic conditions are suitable for the growth of legumes there are often advantages in growing them on soils where large amounts of residues of wide carbon–nitrogen ratio have been plowed under (Thornton, 1929; Pinck et al., 1946; Englehorn et al., 1947). Since they can obtain their nitrogen from the air, their growth is usually not appreciably depressed by the decreased available nitrogen supply in the soil. Whether this practice is economically feasible depends on the legume grown, the yields, and the use made of it. If adding fixed nitrogen to the soil is the chief aim, it is likely to be a questionable procedure; it would likely be cheaper to buy fertilizer nitrogen.

In a large proportion of our farming area, root carbon presents almost the sole source of organic matter available for humus maintenance. This amount of organic matter is usually inadequate to maintain humus at a high level but it may well be adequate to maintain it at the level commonly reached after 50 or more years of continuous farming. After such a period the humus level has commonly stabilized at 30–50% below the virgin level but may still be reasonably adequate for many soils, especially with unlimited supplies of fertilizer available to act as a supplement. In fact, the fertilizer itself by increasing yields also increases root residues, which in turn tend to keep the humus content at a higher level. In many of our soils, where abundant plant food has been added for a number of years, soil organic matter has actually increased, even though no great effort was made to add carbon aside from root carbon to the soil.

Root residues actually have some advantages over top residues as carbon sources. They are intimately mixed with the soil at all times and, as they decompose, the microbial gums produced are well distributed and hence in position to act as cements between soil particles as they are being formed into aggregates by physical forces. When fixed in such aggregates there is much evidence that these polysaccharide gums are protected for a period against oxidation by microorganisms. This stabilization inside aggregates is extremely important since such aggregates are responsible for good tilth, which is usually, or at least often, the primary benefit to be expected from soil organic matter. Of course top residues also constitute sources of these gums but they are never in intimate contact with all of the soil, and the gums produced are decomposed so rapidly that there is only limited movement from the immediate areas where formed. Furthermore, most root residues decompose less rapidly than above-ground residues, and hence serve as a continuous source of polysaccharides for aggregate stabilization.

Animal manures

The use of abundant amounts of animal manures has long been recognized as one of the best methods of fertilizing crops and maintaining productivity and soil organic matter (Prince et al., 1941; Pratt et al., 1957). In fact, for centuries prior to the era of commercial fertilizers animal manures commonly constituted the most important, and often the only, source of plant nutrients other than the soil itself (Olsen et al., 1970).

Recovery of feed nutrients in manure

The recovery in the manure of the fertilizing constituents in the feed varies with the composition and amount of feed, and the age and kind of animal. In the case of dairy cows a considerable portion of the nutrients is recovered in the milk and only a small portion is used for growth. In animals raised for meat the amount of feed nutrients retained for growth is much larger. These facts are illustrated in Table 21.I, taken from Salter and Schollenberger (1939). These data also show that in terms of the three major nutrients, the recovery in the urine is nearly as great as, or even greater than, in the feces. Phosphoric acid recovery in the urine is low but the recovery of nitrogen and potash is high.

Other data tabulated by Salter and Schollenberger for various classes of livestock led them to conclude that generalized values for the recovery of fertilizer constituents in the excrement are as follows: nitrogen, 75%; phosphoric acid, 80%; and potash, 85%: The value for the recovery of organic matter of feed is given as 40%.

TABLE 21.I

RECOVERY AND DISTRIBUTION OF FERTILIZING ELEMENTS CONTAINED IN ANIMAL FEED (from SALTER and SCHOLLENBERGER, 1939)

Distribution	*Percentage recovery*		
	nitrogen	*phosphoric acid*	*potash*
From pigs:			
In feces	21	60	35
In urine	51	23	55
Total excrement	72	83	90
Balance in growth	28	17	10
From cows:			
In feces	40	63	17
In urine	28	1	61
Total excrement	68	64	78
In milk	29	40	20
Balance in growth	3	–4	2

Losses of nutrients during handling

Animal manures are commonly applied to the soil in one of three ways: by direct voiding on pastures or other areas; by hauling of the solid and liquid portions without litter to the field; and by hauling the stable and feedlot manure that contains large amounts of litter added as an absorbent and for keeping the animals clean and comfortable. The efficiency with which the voided nutrients are conserved for crop use varies widely with the system of handling but rarely even closely approaches 100% efficiency because of the many opportunities for losses.

When the feces and urine are voided directly onto pastures, essentially all of the nutrients are conserved, but the efficiency in terms of crop yields may be less than expected because of lack of uniform distribution, accompanied by lack of balance of the major nutrients at any one location. Furthermore, since the solid portion remains on the surface while it undergoes decomposition there are opportunities for loss of ammonia during the process. In actual practice much of the manure that is voided in the open falls under shade trees, along fence rows, and in other areas where the animals congregate and where no crops are growing. There may be almost no economic benefit from much of this voided manure.

In some modern dairies and in systems of mass production of livestock, where the floors of barns or feeding areas are of concrete, the manure may be collected daily and hauled to the field with a minimum of storage involved. Under such conditions it is possible to get almost all of the voided nutrients onto the soil. Losses can be reduced to a minimum if such manure can be incorporated into the soil immediately, or if a growing crop is present to utilize the nutrients. This is not always feasible because of the cropping system or time of the year, and in such cases some storage may be necessary. Manure thrown on uncropped frozen ground during the winter months is usually used very inefficiently.

The largest losses of nutrients commonly occur where stable or barnlot manure, usually containing large amounts of various kinds of litter, is allowed to accumulate for weeks or months prior to application to the soil. Large losses may result from seepage into the soil, and by leaching and volatization of ammonia. Storage in concrete pits under anaerobic conditions serves to reduce such losses very substantially.

Use of manure

Many bulletins have been written on the use of manures, and hence little discussion of the subject is needed here. Manures that do not contain litter and have a carbon–nitrogen ratio of not greater than 25 present few problems whether fresh or well-rotted. If considerable readily-decomposable litter is present, as is usually the case, then some additional nitrogen, and possibly phosphoric acid, may be needed as a supplement. When well-rotted, the manure will yield available nitrogen, and the only supplemental nutrient needed may be phosphorus.

If 60% of the organic matter of the feed is lost as it passes through the digestive system, then it is obvious that the application of freshly-voided manure containing most of the liquid portion to crops is not likely to cause nitrogen deficiency symptoms. It is the litter that consists of plant materials, such as straw and corn stover, that widen the carbon–nitrogen ratio of fresh manures to the point where nitrogen availability is affected.

Value of manure

Prior to the early part of the present century there was evidence that indicated to many research workers that well-rotted manures have plant growth-promoting properties in excess of those attributable to their content of N, P_2O_5 and K_2O. Unknown organic substances, not identified, were believed to be responsible for the observed effects. Further research showed that such intangible effects, when and if observed, were usually due chiefly to minor elements often held in available form by chelation or as exchangeable ions on the organic complex. These minor nutrients can now be supplied at little cost from sources other than manure. As a result, it is now rather generally agreed that the total value of manure is essentially the value of the three major nutrients in the manure plus any value that the user may wish to attribute to the manure as a source of organic matter and chelated minor elements. Manures are of course excellent sources of soil organic matter, and if used in large amounts may actually, over the years, appreciably raise the level of organic matter in many soils. If the other sources of organic matter, especially crop residues, are inadequate under a particular system of farming, then manure as a carbon source may have considerable value; under other conditions this value may be negligible. It is under more intensive systems of agriculture, as in gardening or floriculture, that manures may have maximum value provided the weed seed content does not offset the other values.

Ordinary cow manure from the barnyard is likely to contain about 10 lb. of nitrogen, 5 lb. of phosphate and 10 lb. of potash per ton. The amounts may be more or less than this, depending on the feed and on the way the manure is handled. At 12, 7 and 5 cents per lb. of nitrogen, phosphate, and potash, respectively, the value of such manure is near $2.00 per ton. Poultry manure, which is much higher in nitrogen and phosphate, may be worth $5.00 a ton. Sheep manure is similar in composition to poultry manure, whereas hog manure resembles cow manure. Poultry manure may double in nutrient content if it is allowed to accumulate on the floor of the house until it is thoroughly dry.

The above values would indicate that under many conditions most farm manures, at least cow and pig manures, are too low in nutrient content to justify hauling and spreading (Van Arsdall, 1962). But these waste products constantly accumulate and must be disposed of in some manner. One may therefore consider that on most farms the nutrient value just about offsets the cost of getting rid of the manure. Conservationists, who put great emphasis on avoiding all wastes of natural resources, may not agree with this low evaluation, but it is in line with farm management methods of accounting. The man who owns a small farm, and spends little for outside labor, may also not agree that manure is of so little value. If he spends little for special equipment, and does most of the work of hauling at convenient times, the manure may well be of considerably more value to him than to the one who owns a much larger farm well stocked with livestock.

The low nutrient value of manures, together with the high moisture content of some of them, their odors, and tendency to draw flies has led to increasing interest in disposal by means of lagoons where large numbers of livestock are being raised. These lagoons are used with varying success for the disposition of the more messy wastes, such as pig manure and liquids from the dairy barns. In properly constructed lagoons that have sufficient surface area, microbial oxidation occurs so rapidly and completely that there is little odor or residue.

In his discussion of the disposal of farm wastes Wadleigh (1967) states that "traditionally, the place for manure has been on the land. Recent attempts to dispose of it in lagoons have been unsatisfactory. Additional research is needed to develop more effective systems. Studies indicate that the benefits to soil fertility from manure applications under modern farming conditions do not justify the cost of spreading. But the livestock operator must contend with a daily supply of a product – manure – that he can't sell, can't give away, and can't burn. It is obvious that there is an urgent need to develop more economical ways and means of handling manure to provide some benefit to the land while eliminating possible pollution from farm runoff."

Until better solutions to the problems of disposal of animal manures have been developed, it seems to me that it is best to continue, so far as possible, to follow the age-old practice of returning the manures to the land as directly and efficiently as possible. The soil denatures the wastes more effectively than do other methods, such as the lagoon system. This efficiency, together with the conservation of natural resources, and avoidance of pollution of streams and groundwaters, constitute a strong argument for continuation of past practices even if the expense involved is higher than the value of the nutrients that are conserved.

In this connection it is only fair to point out that many agriculturalists consider manures more valuable than the above discussion would indicate. For example, Buckman and Brady (1969) state that "farm manure is one of the most important agricultural by-products. By its utilization, part of the unused portion of the crop may enter the soil, there to exert an influence far greater than its nutrient content would lead one to expect. The world has already entered an era in which the prevention of agricultural waste is becoming necessary. Therefore, up-to-date farm management demands a more careful handling, as well as a wiser utilization of the manure produced on the farm." This statement, which may be overly optimistic, refers primarily to conditions as encountered on most general farms and not to large-scale operations where hundreds of animals may be kept on comparatively small acreages or in feedlots; that is a special problem.

Composts

Composts (artificial manures) have been in use for centuries, especially in China, India and other Asiatic countries, but also to a lesser extent in western countries (see Chapter 1). The methods of preparation used over the years in China and Japan are well-described by King (1911). Howard (1940) describes at considerable length the composting procedures used in India, including his extensive studies that led to the development of the Indore process.

Regardless of claims as to the merits of a particular method of preparing composts, there is really no one method that is superior. Many methods can be used, and in fact the detailed procedures must be varied in accordance with the raw products available for composting. The basic aim is to bring about rather rapid and thorough decomposition of the organic materials used without undue loss of the nutrients as gases or by leaching, and with the production of an end product that has desirable physical properties. It should also have a final composition such that, when applied to soils, it will gradually release the major and minor nutrients to the growing crop.

The composting process is commonly brought about in the open in piles consisting of alternate layers of organic wastes and other materials including sods, topsoil, peat, sawdust, or other substances that act as absorbents. The addition of animal manure, if available, tends to speed decomposition and helps to improve the texture of the product. If the organic wastes are largely high-carbohydrate materials, some fertilizer nitrogen is needed. Cyanamid, urea, or ammonium salts are preferred sources. In addition, limestone and a source of phosphate should be mixed with the other materials as the compost pile is being constructed.

Since good aeration in the compost pile is essential it is well to mix succulent vegetable wastes with materials that decompose much less rapidly. This prevents packing into soggy anaerobic mixtures. The pile is so constructed that it will catch the natural rainfall or will retain any water that it may be necessary to add from time to time to hasten microbial action. The pile should be turned two or three times during the composting period to increase aeration and bring about a well-mixed uniform product. The decay process is usually completed within three or four months but may be considerably longer depending on the type of wastes used, temperature, moisture, aeration and other factors.

During the period beginning about 1920, when the supply of animal manure was diminishing rapidly, there was increasing interest in the possibility of producing artificial manures from straw, cornstalks, and other materials, chiefly carbonaceous crop residues. Workers in England developed the Adco process for doing this. This process followed along the lines of the older processes except that more nutrients had to be used. For one ton of air-dry plant material a mixture of about 60 lb. of ammonium sulfate, 30 lb. of superphosphate and 60 lb. of finely-ground limestone was added with the plant materials. Although a good artificial manure could be prepared from these carbonaceous residues, the process was never used extensively because of the care and labor involved, and more specifically, because of the advent of the age of commercial fertilizers. These fertilizers could usually act as effective substitutes for either natural or artificial manures, and also increased the quantities of crop residues left to help maintain soil organic matter.

Although the Adco process was developed for the primary reason that a manure substitute was needed, it was also a means of disposing of plant wastes, such as straw, that were known to produce harmful effects on crops when they were incorporated into the soil. It soon became generally known, however, that these bad effects could be almost completely eliminated by the use of adequate nitrogen. Additions of straw, plus enough nitrogen to raise the percentage from about 0.75 to 2.00 or more, allowed the straw to decompose readily in the soil and this mixture usually increased crop growth satisfactorily. This process, sometimes called field composting, essentially eliminated the need for artificial manures for field crops, and markedly reduced the expense and labor.

It was stated in the previous section that for most crops animal manures are barely worth the cost of hauling to the field. It follows that artificial manures, that are commonly of similar value, are also certainly not worth the considerable cost of production plus the cost of hauling if used on field crops. This fact has long been generally recognized and hence their use has been confined largely to garden and greenhouse crops where intensive culture is followed, and where the cost of the artificial manure represents a very small proportion of the total costs. It has been the experience of the writer that their value even here has been greatly overrated, except perhaps in the greenhouse and in soils that are either extremely sandy or heavy. Even in such cases a material, such as peat, supplemented by adequate fertilizer nutrients, may be just as valuable, or more so, as an expensive compost. The city gardener is often urged to conserve his leaves and other plant wastes by composting, but usually the attempt is an almost complete unsightly failure. Satisfactory composting requires much more effort than merely dumping the refuse as it accumulates in a hidden corner without adequate mixing of outside nutrients or adsorbents in the pile, and without much further attention. Unless composting is done scientifically it may be more satisfactory to rely on commercial fertilizers, as the writer has done for many years, and with good success.

The one major exception to the above statements is in the highly specialized art of mushroom growing, where either stable manure or compost is essential. The method of preparing these composts, given by Sinden (1938) and Lambert (1941), is somewhat different than for composts used for other purposes but need not be given here. The total amount of compost used for this purpose is comparatively small.

Composting is also used to a limited extent as a means of disposal of objectional wastes, such as sewage sludge, garbage, canning wastes, and the more messy manures. Usually in such cases the primary aim is the disposal of the materials. Even though the value of the product may be much less than the cost of production, as is usually the case, the composting process may well be justified. Any returns secured help to offset the cost of disposal by other methods, and the wastes are much more satisfactorily disposed of when added to soil than if they are merely dumped into rivers or fills. The increasing use of garbage disposal units in kitchens has resulted in more and more of the city wastes ending up in the sewage and sludge. The sludge has a low content of very slowly available nitrogen. Most of the phosphorus of the original wastes is retained but very little of the potash.

Wood wastes

In many sections of the country wood wastes in the forms of sawdust, bark, or chopped-up limbs are available in large quantities at little or no cost other than hauling. The questions often asked are: of what value are these materials as sources of nutrients and soil organic matter? Are they toxic to plant growth or can they be used satisfactorily as substitutes for crop residues as source materials for humus maintenance? Recent researches in the fields of soil organic matter, soil microbiology and soil aggregation serve as a basis for rather positive answers to these questions.

TABLE 21.II

COMPOSITION OF WOODS AND BARKS OF VARIOUS TREE SPECIES (from ALLISON, 1965)

Species	*Wood*		*Bark*	
	carbon (%)	*nitrogen (%)*	*carbon (%)*	*nitrogen (%)*
Softwoods:				
California incense cedar	51.1	0.097	51.8	0.038
Redcedar	50.8	0.139	46.0	0.206
Cypress	50.3	0.057	47.3	0.324
Redwood	49.9	0.060	48.3	0.060
Western larch	48.6	0.180	49.9	0.161
Eastern hemlock	48.5	0.106	51.1	0.060
Red fir	48.2	0.227	49.1	0.259
White fir	44.8	0.045	51.8	0.135
Douglas fir	48.1	0.051	52.7	0.041
Engleman spruce	48.5	0.118	51.2	0.390
White pine	48.3	0.087	51.5	0.101
Shortleaf pine	45.0	0.130	51.3	0.128
Loblolly pine	48.7	0.068	50.9	0.082
Slash pine	49.2	0.050	52.1	0.056
Longleaf pine	49.9	0.038	50.2	0.092
Ponderosa pine	45.1	0.052	51.8	0.048
Western white pine	48.9	0.113	49.5	0.171
Lodgepole pine	46.9	0.071	49.3	0.179
Sugar pine	50.1	0.124	51.7	0.166
Hardwoods:				
Black oak	47.3	0.070	44.5	0.102
White oak	46.9	0.104	41.6	0.129
Red oak	47.4	0.099	46.2	0.284
Post oak	47.2	0.096	41.8	0.270
Hickory	46.8	0.100	48.1	0.413
Red gum	46.7	0.057	45.1	0.177
Yellow poplar	47.1	0.088	47.6	0.351
Chestnut	47.1	0.072	47.3	0.273
Black walnut	47.0	0.100	45.1	0.177
Averages	48.0	0.093	48.7	0.174

Compositions of woods and barks

The carbon and nitrogen contents of the woods and barks of 19 softwood and 9 hardwood tree species, as reported by Allison (1965), are given in Table 21.II. According to these data the carbon contents of the woods varied between 44.8 and 51.1% with an average value of 48.0%; the corresponding range for the barks was 41.6–52.7% with an average of 48.7%. The nitrogen contents were 0.038–0.227% for the woods with an average of 0.093%; the corresponding values for the barks were 0.041–0.413% with an average of 0.174%. The average carbon–nitrogen ratios of the woods and barks were 516 and 280, respectively. For comparison, wheat straw commonly contains about 0.4–0.75% nitrogen and 40–45% carbon, making the carbon–nitrogen ratio within the range of about 60–110. Green manure crops commonly have carbon–nitrogen ratios of 10–20. These values emphasize how extremely deficient woods and barks are in nitrogen. The content of potash and lime in woods is about the same as that of nitrogen, whereas the phosphoric acid content is likely to be even lower.

Decomposition

There is a wide difference in the rate at which different kinds of woods and barks are decomposed with the release of carbon as carbon dioxide. It is this difference that largely accounts for many statements in the literature that appear to be contradictory. Unfortunately in much of the literature reference is made to experiments with, or to the practical use of, sawdust without any indication of the wood species involved.

Experimental data, showing the extent of decomposition in 60 days of the 28 wood species listed in Table 21.II, are given in Table 21.III. These experiments were conducted in a sandy loam soil of medium fertility. Since the effect of added fertilizer nitrogen was under study, the soil was leached with water prior to use in order to remove any nitrate nitrogen present.

The data in Table 21.III show the very great variability in ease of decomposition of different kinds of woods and barks. During the 60-day period the percentage release of carbon as carbon dioxide varied between 1.5 and 51.0% for woods, and between 2.1 and 42.0 for barks. With such a difference it is obvious that in decomposition studies the wood species must be named if the results are to have much meaning. The big difference in susceptibility to decomposition is between softwoods and hardwoods, the latter, on the average, being much more easily attacked than the former. Shortleaf pine, a softwood, was an exception since it was the most easily decomposed of all of the wood species. On the average, barks behaved as did the woods but were more resistant to microbial attack.

In experiments with 8 species, lasting for 365–800 days, 21–65% of the wood carbon was lost as carbon dioxide and 8–55% of the bark carbon (Allison, 1965). In some cases limited decomposition during the first two months was followed by marked decomposition later, suggesting that toxic substances may have been present that delayed biological attack initially. The addition of fertilizer nitrogen (see Table 21.III) usually increased carbon dioxide evolution markedly from the woods and barks that were decomposed

TABLE 21.III

PERCENTAGE OF CARBON RELEASED AS CARBON DIOXIDE FROM WOODS AND BARKS INCUBATED IN SOIL FOR 60 DAYS (from ALLISON, 1965)[*1]

Tree species	*Wood carbon released as* CO_2		*Bark carbon released as* CO_2	
	no nitrogen added (%)	*nitrogen added*[*2] *(%)*	*no nitrogen added (%)*	*nitrogen added*[*2] *(%)*
Softwoods:				
California incense cedar	4.2	4.9	6.5	5.0
Redcedar	1.5	3.9	17.7	18.2
Cypress	3.8	3.6	5.9	4.5
Redwood	3.8	5.3	2.1	2.1
Western larch	14.7	11.7	5.6	4.8
Eastern hemlock	7.5	3.4	6.1	4.2
Red fir	15.4	8.0	9.0	7.5
White fir	16.2	11.8	10.4	7.9
Douglas fir	11.2	8.4	10.6	7.8
Engleman spruce	19.0	15.1	15.0	16.1
White pine	16.4	9.5	3.6	3.0
Shortleaf pine	25.2	51.0	4.4	4.1
Loblolly pine	17.0	8.6	3.6	3.5
Slash pine	16.8	15.5	7.3	5.5
Longleaf pine	16.4	13.8	9.0	9.3
Ponderosa pine	13.7	10.2	9.6	11.1
Western white pine	16.2	22.2	12.6	13.8
Lodgepole pine	16.3	12.9	23.3	23.2
Sugar pine	7.8	8.0	5.0	3.8
Averages:	12.8	12.0	8.8	8.2
Hardwoods:				
Black oak	24.9	46.5	21.3	25.3
White oak	38.1	49.1	27.4	26.4
Red oak	31.9	43.3	22.9	32.2
Post oak	28.1	42.1	23.2	26.2
Hickory	33.7	48.1	11.7	9.6
Red gum	31.3	48.9	21.2	20.0
Yellow poplar	30.6	44.3	37.5	42.0
Chestnut	26.6	38.5	23.1	27.6
Black walnut	27.1	44.7	13.7	11.4
Averages:	30.3	45.1	22.4	24.5
Averages, all species	18.5	22.6	13.2	13.4

[*1] Comparative studies showed a release of 54.6% of the carbon of wheat straw as CO_2 in 60 days.

[*2] Nitrogen additions were in the range of 0.75–2.0% of the weight of added wood.

most readily but had a negligible effect on the other tree products. This is in harmony with frequent observations showing that nitrogen needs parallel the rate of decomposition of plant materials. In these experiments some available nitrogen was present, even where no fertilizer nitrogen was added, since the woods and barks were incubated in soil, and all normal soils release nitrogen during incubation. Where decomposition was slow, the soil alone supplied as much available nitrogen as needed for a maximum rate of biological attack.

Nitrogen immobilization

Since woods and barks have very wide carbon–nitrogen ratios, and even the small amount of nitrogen present is not readily available to microorganisms, it is necessary that there be an outside source of nitrogen if decomposition is to proceed at a reasonably rapid rate. The outside nitrogen source may be obtained from the soil itself, from fertilizers, or from any other added materials that release their nitrogen readily. If the rate of decay of the wood products is very slow, then the nitrogen requirements are negligible. In fact, rate of decay and rate of nitrogen uptake are so closely correlated that either process is a measure of the other (see Fig.6.4).

The quantity of nitrogen immobilized by 28 wood species during decomposition periods of 10–160 days, as reported by Allison (1965), are shown in Table 21.IV. Wheat straw is also included for comparison. All tests were made in soil with the inclusion of untreated soils for controls, and the nitrates formed in these controls subtracted from the nitrates in the treated soils in order to obtain net immobilization values. The maximum nitrogen immobilization ranged between 0.3 and 1.4% of the dry weights of the woods, with an average value of 0.8%. The comparative value for wheat straw is 1.7%. The nitrogen required averaged 0.6% for the softwoods and 1.2% for the hardwoods. All of the 9 hardwoods had nitrogen requirements greater than 1.0%, but only one softwood had a value this high. Maximum nitrogen requirements were usually observed within 40–80 days for the most readily decomposed woods, but the more resistant woods usually continued to immobilize nitrogen slowly until the end of the experiment. The maximum value for wheat straw was recorded at the end of 20 days.

In studies of the decomposition of sawdusts in soils at 78°F., McKenzie (1958) observed that the maximum amounts of nitrogen taken up by mountain ash (*Eucalyptus regnans* F. Muell), red ironbark (*Eucalyptus sideroxylon* A. Cunn) and radiata pine (*Pinus radiata* D. Don) were 1.6, 1.4 and 1.0% respectively. He states that "it is possible that these amounts are inversely related to degree of lignification of the wood, and this would account for softwoods causing less uptake than eucalypts, and a dense eucalypt less uptake than a less dense one." Maximum uptake was reached in 5–11 weeks and the immobilized nitrogen was released very slowly over a period of many weeks.

The nitrogen that is immobilized during the decomposition of wood products, like other organic sources, is the nitrogen needed for the multiplication and growth of the living organisms that are responsible for decay. In the early stages of the process there may be a slight release of the assimilated nitrogen but after a few months this nitrogen

TABLE 21.IV

NITROGEN IMMOBILIZED BY MICROORGANISMS IN THE DECOMPOSITION OF VARIOUS WOOD SPECIES IN SOIL (from ALLISON, 1965)

Tree species	*Percent nitrogen immobilized after:**				
	10 days	*20 days*	*40 days*	*80 days*	*160 days*
Softwoods:					
California incense cedar	0.17	0.25	0.52	0.69	0.52
Redcedar	0.17	0.22	0.17	0.28	0.41
Cypress	0.13	0.08	0.17	0.25	0.37
Redwood	0.13	0.22	0.21	0.31	0.34
Western larch	0.20	0.21	0.44	0.64	0.79
Eastern hemlock	0.08	0.08	0.20	0.35	0.42
Red fir	0.22	0.14	0.36	0.54	0.83
White fir	0.04	0.00	0.25	0.35	0.54
Douglas fir	0.07	0.21	0.07	0.14	0.30
Engleman spruce	0.15	0.06	0.48	0.69	0.74
White pine	0.08	0.05	0.29	0.48	0.41
Shortleaf pine	0.78	1.00	1.27	1.30	1.13
Loblolly pine	0.01	0.15	0.31	0.63	0.60
Slash pine	0.04	0.02	0.17	0.46	0.64
Longleaf pine	0.01	0.00	0.15	0.30	0.49
Ponderosa pine	0.05	0.07	0.19	0.44	0.42
Western white pine	0.11	0.08	0.35	0.61	0.89
Lodgepole pine	0.07	0.01	0.29	0.61	0.80
Sugar pine	0.13	0.15	0.33	0.43	0.54
Averages	0.14	0.16	0.33	0.50	0.59
Hardwoods:					
Black oak	0.86	1.17	1.21	1.20	1.05
White oak	0.62	0.96	1.19	1.15	1.09
Red oak	0.93	1.20	1.40	1.23	1.16
Post oak	0.77	1.07	1.27	1.25	1.20
Hickory	0.78	1.00	1.12	1.17	1.07
Red gum	0.90	1.28	1.24	1.18	1.04
Yellow poplar	0.98	1.19	1.13	1.15	1.05
Chestnut	0.38	0.88	1.14	1.07	1.13
Black walnut	0.80	1.18	1.20	1.15	1.07
Averages	0.78	1.10	1.21	1.17	1.10
Averages, all woods	0.35	0.46	0.61	0.72	0.75
Wheat straw	1.25	1.68	1.35	1.14	–

*In percentage of dry weight of wood. To obtain nitrogen immobilization values per ton of wood, multiply percentage figures by 2,000. This gives values of about 5–25 lb. N for the various woods.

has become so thoroughly incorporated into the soil organic matter being formed that only a very small part of it is then released at any one time. In other words, it has become a constituent of humus. Only nitrogen in excess of that tied up in the process of decomposition is readily available tc a crop that may be growing on the soil.

Toxicity

Additions of sawdust and barks in quantity to soils have frequently been shown to inhibit plant growth. It has been shown repeatedly that such effects are usually the result of nitrogen deficiency. Since sawdust and barks require from 5–25 lb. of nitrogen per ton (see Table 21.IV) to meet the needs of the microbial flora, it is obvious that few if any soils can furnish this amount of available nitrogen in addition to that needed by the crop. Applications of 5, 10 or even more tons per acre of wood products are not unusual, especially when used as mulches. Furthermore, periodic rainfall may leach applied fertilizer nitrogen into the subsoil and thereby increase the nitrogen-deficiency symptoms. Unless this needed nitrogen is supplied, the harmful effects of the more readily decomposable sawdusts can be very marked. In extreme cases there may be only a dwarfed, yellowish type of crop produced. This effect is of course similar to that produced by other carbonaceous plant residues but often much more extreme because of the very low nitrogen contents of woods and the larger rates of application often used. These effects, strictly speaking, are not toxicity symptoms, since toxicity results from the presence of a harmful material rather than from the absence of an essential nutrient.

Wood wastes do sometimes contain substances that are toxic to plants. In the studies with the 28 species of trees, Allison (1965) reported that most of the woods and barks were not toxic, but California incense cedar and white pine bark were very toxic to garden peas even at the rates of 1 and 2% added to soil in the presence of adequate nitrogen and lime. The woods of red cedar, Ponderosa pine, and loblolly pine, and the barks of California incense cedar and yellow poplar were slightly toxic at the 2–4% rates. The toxicity symptoms usually decreased with time during the two- to three-month period following addition to the soil. There have also been reports that a few other woods, such as walnut, hemlock, fir, and balsam are sometimes, but not always, toxic. Toxicity seems to vary with the age of the tree, and is also dependent upon the quantity added and the test plant. Decomposition time curves, reported by Allison, indicate that it is not uncommon for wood products to slightly retard early decomposition, apparently until the toxic materials disappear. The chemical nature of any toxic products present is not known with certainty but some investigators have attributed the toxicity to resins, turpentine and tannins.

Toxicity, although encountered occasionally, is not a very serious factor in the use of wood products as humus sources in the presence of adequate nitrogen and lime, if needed. The few wood products that are known to be toxic should be avoided, or sufficient time after application to soil should be allowed for considerable biological decomposition to occur before crops, particularly seedlings, are exposed to them.

Value as humus sources

There has been considerable uncertainty over the years as to the value of wood products as humus sources, although their merits as mulches have been reasonably well evaluated. Their value as a humus source has been questioned primarily because of their deficiency in nitrogen. But considerable uncertainty has also existed as to their merits even where adequate supplemental nitrogen was supplied.

Even under ideal soil conditions most wood products are commonly decomposed only slowly, leaving for a time chiefly lignin in intimate association with celluloses and hemicelluloses. In the past, when great emphasis was placed on lignin as a constituent of humus, there were some investigators who apparently considered this accumulation very desirable regardless of inertness. More recent research has shown, or at least strongly indicated, that humus consists largely of residual microbial materials rather than of residual plant materials. According to this view, degradation proceeds at various rates, usually rapid at first and then at a continually decreasing rate, until practically all of the original plant materials not lost as gases are assimilated by microorganisms, or at least so radically changed that they bear little resemblance to the original plant substances. Lignin is the most resistant of all plant substances, but it is not immune to microbial attack.

Assuming that most plant carbon in soil that is not evolved as carbon dioxide passes through microorganisms on its way to humus it would seem that, in the presence of adequate nitrogen, wood carbon should be nearly as satisfactory a source of humus carbon as are other plant sources. Wood should serve as an especially abundant source of heterocyclic compounds needed for polymerization, along with amino acids, into humus. On the other hand, the slow rate of decomposition of woods might lead to a marked loss of carbon as carbon dioxide, leaving a smaller percentage for microbial cell synthesis than where carbon sources undergo rapid decomposition. For example, studies have shown that during short periods (2–4 days) as much as 30–60% of sugar carbon may be converted into cell substance by some microorganisms, but if the study is continued for several days the total cell substance produced per unit of carbon utilized may be only half the initial amounts. We must await further research before we can state accurately the value of wood products in comparison with other carbonaceous materials as sources of humus, but present evidence indicates that they are probably not as valuable even if the nitrogen supply is adequate. This is probably because of lack of amino acids in close association needed for combination and polymerization with ring compounds to form humus. Wood products are of very little value as sources of active humic materials.

In terms of economics or cost accounting, no wood products may be worth hauling to the field. Since their nutrient value is negligible, almost their whole value is dependent upon the value put on them as mulches and as humus sources. The situation here is even more unfavorable than for animal manures, discussed above; the latter at least have a considerable nutrient value per ton even though the moisture content is much higher.

Peat

Peat is a very valuable material for use in vegetable and flower gardens, as every gardener knows, but its value is primarily as a mulch and for improving soil tilth in heavy clay soils. It also adds to the exchange and absorptive capacity of the soil, adds some available nutrients, and helps to hold nutrients in available form. We are less certain as to its value as a humus source.

Peat is the residual product of sedges, grasses, mosses, twigs, etc. that have been allowed to decompose partially and slowly under near-anaerobic conditions, and usually under water, for many years or centuries. During this period apparently changes in the carbon compounds occur that increase their resistance to decay after they are exposed to the air. The loss of carbon from peats after addition to soil may be no more than 10% during the first year. They are considerably less readily decomposed than are most woods. Their suitability as sources of resistant humus is doubtless good but they have little value as active humic materials. Here, again, quantitative data are lacking but doubtless most of the peat carbon, not released as carbon dioxide, will eventually pass through microorganisms. Residues of microorganisms are much alike regardless of their foods.

The effect of peat on bulk density of heavy soils is a very important one regardless of its contribution to either active or inactive humus. It helps to maintain good aggregation, prevents clod formation, improves aeration and water infiltration, and permits an easy and wide ramification of plant root systems. Cultivation is done with much less difficulty. In very sandy soils peat increases the retentive capacity for both water and nutrients.

A more extensive discussion of peat, its uses, and value in crop production is given in Chapter 29 and 30.

Green manures

Since green manures are discussed at some length in the chapter that follows, only brief reference to them need be given here. Suffice it to say that green manures are seldom grown for the primary purpose of maintaining or increasing total soil organic matter. They are often grown for the purpose of increasing very active organic matter even though in the process there may be no gain, or even a slight loss in total organic matter. This failure in net gain in total carbon is chiefly the result of decomposition of native soil organic matter that occurs during the time the green crop is on the soil and is attributable to the increased oxidation following the stirring of the soil.

Although green manure carbon is rapidly oxidized by the soil microorganisms there is little evidence that this carbon is any less valuable in humus formation per unit of carbon added to the soil than is carbon from more carbonaceous crop residues (Pinck et al., 1950; Giddens et al., 1965). This is contrary to past prevailing opinion (Russell, 1961) which considered green manure carbon to be decomposed so rapidly and completely that little was left to contribute to total organic matter. It does decompose rapidly but the residual end products seem to be very well suited for rapid humus formation.

Sod crops

The best-known method of maintaining or increasing soil organic matter is by keeping the soil in grass or grass–legume mixtures continuously, or at least for as large a percentage of time as practicable. The carbonaceous materials that are thus added to the soil are excellent sources of both active organic and more resistant, large-molecule, types of soil organic matter. The tendency toward a build-up of organic matter is attributable chiefly to the comparatively large amount of new carbonaceous materials added to the soil, to the lack of stirring of the soil, to the presence at all times of a growing crop, and to the elimination of erosion and leaching. Even if the crop is removed as hay, or by grazing, the mass of roots serves as an excellent source of humus. This subject is discussed further in the chapter that follows.

FACTORS THAT AFFECT THE ORGANIC MATTER CONTENT OF CROPPED SOILS

In the present age of abundant commercial fertilizers, good crops can be grown on soils of any organic matter content provided climatic conditions are satisfactory, adequate moisture is maintained, and the essential nutrients are supplied in needed amounts. Regardless of these facts, a good supply of organic matter is always prized by the farmer. This brings up the matter of what constitutes a good supply, and what are the factors that determine the level that can, or should be, attained. The principal factors commonly encountered are considered as follows.

Kind of soil

The nature of the soil itself is the factor of primary importance in determining the percentage of organic matter that a soil will retain under cropping conditions. A very sandy soil may contain only 1% organic matter, whereas under similar climatic and cultural conditions a clay soil may retain 5% or more organic matter. There is usually a close direct correlation between clay content and organic matter content. The kind of clay is also a factor of importance; the three-layer clay minerals, especially montmorillonite, are somewhat more retentive of carbon than are the two-layer minerals, such as kaolinite. These colloidal minerals combine with organic matter so tenaciously, that complete separation requires drastic chemical treatments so that either the mineral or the organic matter is dissolved or radically changed in the process. The comparatively high content of organic carbon in clay soils is due in part to this tie-up with the mineral but also to other factors, including decreased aeration, retarded water movement, and high adsorptive capacity. If the clay soils are well aggregated, considerable organic carbon may be held inside the aggregates, where it is largely protected against microbial attack, just as is the case with organic substances held in interlamellar spaces of three-layer minerals.

Previous history of the soil

All soils that are exposed to a constant set of conditions for long periods respond to these conditions by fixing an amount of organic matter, or humus, that reflects the nature of the soil, the climatic conditions, and the kind and amount of plant cover. In other words, the soil comes to terms with nature. Such an equilibrium, or steady state condition, may not be reached for hundreds of years under virgin conditions where the soil is left undisturbed. In other instances a period as short as 50–100 years may be adequate for the establishment of an organic matter level that is perhaps 90% of the climax level. There is a tremendous difference in the rate at which equilibrium is attained, but ordinarily any build-up of organic matter from a very low to a higher level is likely to proceed rapidly during the first 25% of the build-up period and then at an ever decreasing rate thereafter for centuries. Actually, a climax level may never be reached – only approached – since conditions in nature almost never remain constant for centuries.

When a virgin soil is put under cultivation the organic matter content usually decreases to perhaps 50–60% of its climax level within a period of 25 years, and the oxidation is likely to continue at a decreasing rate for many additional years. The extent to which the organic matter level is lowered is dependent upon all of the environmental factors just as when the organic matter is being raised. The soil must now come to terms with nature and with whatever modifications of nature man has introduced.

When we discuss the matter of maintenance or build-up of organic matter, it is therefore essential that we know where we are on this descending scale. Under normal farming conditions, soil organic matter can obviously never be maintained at the climax level. Ordinarily we must deal with a soil that is at an organic matter level much lower than this, and its lowness largely sets a limit as to what we can do to change it. If the soil has been "worn out" by 100 years of poor management, and the carbon level is at a third of the virgin level, then obviously the introduction of good farm management practices may be expected to raise the level appreciably. On the other hand, if the soil organic matter level is at 50–75% of the virgin level, the introduction of excellent farm management may do no more than maintain this level. In fact, it may not even do this for the trend downward from the climax level may not have gone far enough to permit stabilization. There is no arbitrary organic matter level that must be maintained. What is needed is adequate organic matter, and adequate is a variable quantity that usually cannot be arrived at on theoretical grounds. The farmer may be able to define the term better than the scientist in the laboratory.

Temperature and moisture

Soil organic matter under conditions prevailing in the United States tends to increase as the temperature decreases and as the moisture increases, as Jenny (1930) has pointed out. He stated that for each fall of 10° C in annual temperature the nitrogen and organic matter content of soils increases 2–3 times. The carbon–nitrogen ratio may also increase with the total organic matter. The increase in organic matter with that in rainfall is in part a reflection of increased yields where moisture is abundant, but soils also differ in many respects.

Temperature and moisture effects are major factors in determining the organic matter level in both virgin soils and in cultivated soils. It may be a simple matter to maintain a 4% level of organic matter in northern United States soils, but almost impossible to maintain half this level in many of the southern soils where it is very much needed. Oxidation is so rapid at higher temperatures that it is often very difficult to maintain even 2% organic matter in these soils.

In more tropical soils, as in Puerto Rico, many of the soils are as high in organic matter as are some of the best soils of temperate regions. Smith et al. (1951) suggest that this can probably be attributed to the absence of killing frosts in these regions. Undoubtedly this is a very plausible explanation, for living tissues are not subject to microbial decomposition that proceeds so rapidly in warm climates after death occurs.

Tillage

Soils that are plowed and cultivated frequently over a period of years almost invariably contain a considerably smaller percentage of organic matter than those that are subjected to a minimum of disturbance, or are left permanently in grass or other perennial crops. Tillage increases aeration, oxidation, leaching and erosion. Furthermore, plowing kills any plants that may be present, and dead plants decompose rapidly. Green plants also continually add new organic matter, even if in limited amounts. Cultivated soils are also subject to periodic wetting and drying, and it has been demonstrated repeatedly that drying makes available considerable organic matter that is held bound to clays or inside clay lattices. This is strikingly demonstrated by the burst of evolution of carbon dioxide that occurs after each wetting of dried soils. This effect is more in evidence in soils of finer texture.

Amount of plant material added

Large amounts of crop residues, continually added to soil, will tend to make the soil organic matter level higher than where much smaller amounts are added, but the difference may not be in direct proportion to the amount of carbon added. This is in harmony with the well-known fact that the higher the level of organic matter the more difficult it is to maintain or increase it. It is also true that many soils have a limited capacity for retaining carbon.

When crop residues are added to a soil of medium texture under good climatic conditions, experiments (Siegel, 1940; Allison et al., 1949; Pinck et al., 1950) have shown that only about 30% of the added carbon will be present in the soil after one year, perhaps 15–20% after two years, and 10–15% after three years. This process continues at a much slower rate in subsequent years.

Experimental data reported by Peevy and Norman (1948), given in Table 21.V, show somewhat lower carbon retention values than those given above. The experimental conditions, particularly the temperature of incubation and the texture of the soil, are important in such studies. The data in Table 21.V emphasize the rapidity at which the carbon loss occurred initially and the slow rate of change after the first year.

TABLE 21.V

CHANGES IN ORGANIC CARBON IN A LIMED THURMAN LOAMY FINE SAND RECEIVING 10% ORGANIC MATERIALS (from PEEVY and NORMAN, 1948)

Organic materials added		*Percent of added carbon retained by soil after:*			
	C/N ratio	*105 days*	*328 days*	*580 days*	*833 days*
Oat straw	29*	31.4	16.0	13.8	12.4
"Cellulose" from oat straw	29*	18.3	13.2	11.6	7.4
Dextrose	29*	4.0	2.5	2.5	2.8
Alfalfa	13	35.7	16.4	16.0	15.5
Soybean stalks	62	47.8	14.3	14.1	13.4
Soybean stalks	29*	57.2	14.7	15.6	13.4

*Ammonium nitrate added.

Organic matter, added as plant residues, may be retained in soil for awhile as residual undecomposed plant materials and as microbial cells. In addition, as decomposition proceeds, compounds, such as polysaccharides, amino acids, and low molecular weight humic materials, are formed that may be held in or on colloidal clays, or be inactivated in soil aggregates. Simultaneously, or later, considerable chemical polymerization may occur involving primarily amino acids and heterocyclic compounds with the formation of high molecular weight materials that we designate as stable humus. Only the latter-type material seems to be resistant to microbial attack because of its chemical and physical constitution; the other low-molecular weight substances are dependent upon close association with colloidal inorganic material for protection against microorganisms and their enzymes. This is the primary reason why sandy soils, which have low amounts of inorganic colloids, retain very much smaller amounts of organic matter than do clay soils. As soil inorganic colloids adsorb all of the organic colloids that can combine with them, any unprotected organic matter is more susceptible to further decomposition.

Kind of plant material added

Plant materials that are woody and resistant to decay show higher accumulations of organic matter in soils than do more succulent materials during experimental periods of 1–2 years. During longer periods there is little evidence that this relationship holds; in fact, there is considerable qualitative evidence that woody materials are less suitable as humus sources than are the more readily decomposable materials. Here, we must distinguish between total organic carbon in soil, not all of which is well decomposed, and humus carbon that has lost its plant identity.

If it be granted that much, or perhaps most, of the plant carbon that finally ends up as humus passes through microorganisms, as present evidence seems to indicate (Turin and Kononova, 1962; Swaby and Ladd, 1962, 1966; Kuo and Bartholomew, 1966), then it follows that plant materials that are easily decomposed reach the humus stage sooner than woody materials. There might be little difference in total humus ultimately formed, but only in how soon it forms. Woody materials contain more lignin and less protein than succulent materials, and this may be an important factor since heterocyclic compounds, formed by microorganisms from lignin, and amino acids are involved in humus synthesis. Lack of nitrogen in the woody materials may not be overly important, however, for the organisms that decompose these materials would use soil nitrogen to make up for any deficiencies. Present evidence scarcely justifies being dogmatic on this poorly-understood phase of humus formation.

Amount of nitrogen added

Prior to the publication of the articles by Allison (1955) and by Bartholomew (1955) frequent statements were made to the effect that when very carbonaceous crop residues are added to the soil considerable nitrogen fertilizer should also be added to hold the carbon, and thus produce much more humus. This idea originated chiefly from data showing that additions of nitrogen to field soils does help to maintain organic matter at a higher level than where no nitrogen is applied. This is the result of larger yields, and larger crop residues (Barbier, 1959), and is not because nitrogen additions reduce the losses of carbon as carbon dioxide during decomposition; they do not appreciably do this.

Where nitrogen is very deficient, its addition may increase the rate of decay somewhat but this has little effect on total carbon dioxide evolution. Actually, the added nitrogen is unlikely to even increase the rate of oxidation because all normal soils are constantly releasing available nitrogen under climatic conditions that are favorable for bacterial action. If the residues do not supply the microorganisms with enough to meet their needs, they merely use the nitrates formed from the soil. It would be only soils of extremely low fertility that would not be able to supply much nitrogen and, of course, these soils would also not produce much crop or crop residue. Straw or cornstalks that contain 0.75% nitrogen would require only about 15 lb. of outside nitrogen per ton for their decay; if they contained 1% nitrogen only 10 lb. of outside nitrogen per ton of residue would be needed.

The general conclusion is that it is not profitable to apply nitrogen to soils in order to rot residues. All nitrogen should be applied to the crop at such times as is best suited to the growing of the crop. If carbonaceous residues have been applied, then enough nitrogen should be added to meet the needs of both the crop and the decomposition process that takes place just prior to planting or while the crop is growing. Where crop residues are decomposing in a compost pile, some fertilizer nitrogen may be needed, but even here it is used not to reduce gaseous losses of carbon but rather to hasten decay and to produce a better product.

Fire

The annual burning of forest and grasslands is, or has been, a common practice in many places in the Tropics and also in the southeastern part of the United States. In addition, slash burning is often practiced at times in forests, such as the Douglas fir region. Fire is used of course primarily because it is a quick and easy method of ridding the land of unwanted organic debris. In parts of the Tropics where the amount of grass or tree debris per acre is large, and mechanical means of coping with it are limited, burning is often almost the only practical way to clear the land for crops. In regions where trees are being harvested, the burning of brush piles is common in order to prepare the land for more tree planting or for other vegetation. In the southeastern United States burning eliminates much of the surface accumulation of pine needles and permits the quick growth of grasses and sometimes of legumes. This annual burning affects only the surface one to two inches of soil.

In his discussion of conditions in Brazil, Baldanzi (1960) states that the burning of plant residues before cultivation is a common farming practice. Under these tropical conditions the ground is always covered with vegetation and there is a continuous and abundant accumulation of residues, and a high organic matter content, although qualitatively poorer than that of the soils in temperate climates. He states that "ploughing under a great mass of dry grass residue (about 10–15 ton/ha) of high C/N relation immediately before sowing causes a depression in crop production and does not benefit the fertility of the soils. Of the two alternatives (burning off or ploughing under) for making use of the plant residue, burning appears advisable. Nitrogen fertilization is not very efficient and often not economical. After three years of experimentation no significant decrease or increase of carbon or nitrogen in soil has been observed in consequence of the various experimental treatments. On the other hand, the carbon and nitrogen content of the soil continues high."

Greenland and Nye (1960) studied the effect of straw on nitrate levels in tropical soils of Ghana that received two dressings of 10 tons each of cereal straw annually both with and without 100 lb. of ammonium sulfate per acre. The straw was either ploughed in, burned, or used as a mulch. They summarized their results as follows: "Only very small differences (1–2 p.p.m.) of nitrate nitrogen were found following the incorporation of straw, whether or not ammonium sulphate was applied. Observations on the crop confirmed that little immobilisation of nitrogen was occurring. There was also little evidence of nitrogen immobilisation under the mulch. Slow decomposition, significant nitrogen fixation during decomposition, decomposition by termites and bacteria involving an exceptionally low nitrogen demand, and concentration of straw so that the bulk of soil remains unaffected, are suggested as reasons for the low immobilisation. An increase of nitrifiable nitrogen was found to occur if the straw was used as a mulch, but not if it was ploughed in or burnt."

When first observed, one is likely to consider burning a very wasteful process, particularly in temperate regions, and one that is very harmful to soil fertility. Whether this is true or not depends in large part on the severity and frequency of burning and on the use made of the land following burning (Heyward and Barnette, 1934, 1936; Garren, 1943; Tarrant, 1956; Klemmedson et al., 1962). Tarrant states that in the Douglas fir region severe burning does damage some soil properties, but the soil surface affected by severe burning usually represents only a small portion of the total area logged and burned, and these areas are decreasing as more use is being made of the low-grade materials.

In the southeastern United States, Heyward and Barnette point out that in the longleaf region where there is no burning it is common for pine needle litter to accumulate to a depth of 2–3 inches, preventing the growth of ground cover consisting of wiregrass and various herbaceous plants including legumes. These furnish good pasturage for livestock. Burning that removes surface organic matter may eventually result in slight increases in soil organic matter at lower depths if the practices followed permit the growth of the ground cover for a considerable portion of the time. Nitrogen that is lost through burning may be more than replaced by legumes. Burning also decreases soil acidity as a result of the addition of ash, thereby making the environment more favorable for legumes. Unfortunately, the mellow, permeable surface soil (on unburned areas) is, as a result of burning, sometimes changed into a more compact and impermeable soil. The magnitude of this physical change varies with soil texture, amount of organic litter present and with severity of the burning.

Burning is, therefore, usually less harmful to soil organic matter and soil fertility in forested areas than one might expect, and may even at times be beneficial in an indirect way if good cropping practices that were prevented by litter are made possible.

SOME PRACTICAL CONCLUSIONS

The discussion in this and previous chapters has served to emphasize that so far as humus maintenance is concerned each soil is to a considerable extent an individual case. The use to be made of the soil is also a major factor. In fact, adjusting the cropping system to fit the soil is a very practical way of utilizing problem soils. For example, a fine-textured soil of low organic matter content and very poor physical condition might be unsatisfactory for use in general farming, where a standard crop rotation is used. However, the same soil might produce excellent hay crops and in doing so gain in organic matter content, become well aggregated, and show greatly improved water relationships and tilth.

There is no specific required organic matter level for soils even if they are of the same texture and located in the same climatic zone. This is because organic matter is only one of many factors that determine their suitability for agriculture. Other factors, such as drainage, kind of clay mineral, nutrient level, and past management may be at least as important. The use to be made of the soil is also an important consideration. An organic matter level that is satisfactory in a soil that is to be used for general farming may be inadequate if the soil is to be used for gardening.

The organic content of agricultural soils in the United States is now much below the climax level because they have been under cultivation for at least 60 years, and most of them for 100 to 300 years. This assures that their organic matter content is nearly stabilized at whatever level past management has brought about. Increased use of fertilizers, together with improved management in recent years, has actually not only stopped the downward trend in most soils but has brought about some reversal of the process. This means that now we need not be as seriously concerned about loss of soil organic matter as we were prior to the age of commercial fertilizers when we were so dependent on soil organic matter for nutrients. It is still very important but for other reasons that vary for soils and for cropping systems.

The long-standing recommendation that all crop residues be returned to the soil to insure organic matter maintenance is still a sound one, but the emphasis is now more on root residues and less on top residues, at least in regions of adequate rainfall. This is a logical follow-up of the revolution that has occurred in recent years in farming; heavy fertilization with some changes in cropping systems has demonstrated that in many soils roots alone are adequate for the maintenance of a satisfactory level of soil organic matter. Where crops, such as corn that have fairly extensive root systems, are grown frequently, not only do the roots serve as precursors of soil organic matter but the roots themselves during growth increase soil aggregation. The roots, directly or indirectly, help markedly in aggregate formation, and the polysaccharides and humic substances formed during their decomposition help materially in stabilization of the aggregates. This two-fold action of extensive root systems has probably not been sufficiently emphasized in past writings. In this situation the roots play a major role in bringing about good tilth long before microorganisms have decomposed them to the stage of humus. Both active organic matter, as described above, and true humus are essential for good soil aggregation and structure but their relative importance varies from soil to soil.

The tendency in recent years to grow crops by methods that involve the minimum amount of tillage is helping markedly in the maintenance of organic matter at adequate levels. This partial approach to conditions that existed when the soils were in their original virgin condition means that a given level of organic matter can now be maintained in soils with additions of considerably smaller amounts of crop residues than formerly required. This change in farm management practices was one of the results that followed the extensive use of commercial fertilizers. Decreased emphasis on the necessity for having legumes in the rotation was another result of the making available of other sources of nitrogen at favorable economic levels.

REFERENCES

Allison, F.E., 1955. *Soil Sci. Soc. Am., Proc.*, 19: 210–211.
Allison, F.E., 1965. *U.S. Dep. Agric., Tech. Bull.*, 1332: 1–58.
Allison, F.E., Sherman, M.S. and Pinck, L.A., 1949. *Soil Sci.*, 68: 463–478.
Baldanzi, G., 1960. *Int. Congr. Soil Sci., 7th, Madison, Wisc., 1960, Comm.*, III: 523–530.
Barbier, G., 1959. *Commun. World Fert. Congr., 3rd, Heidelberg, 1957*, pp. 55–65.

Bartholomew, W.V., 1955. *Agric. Chem.*, 10: 38–40, 97–99.

Bartholomew, W.V., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy* 10: 285–306.

Bartholomew, W.V., 1966. In: *The Use of Isotopes in Soil Organic Matter Studies.* Pergamon, New York, N.Y., pp. 171–183.

Bradfield, R., 1954. *Soil Microbiol. Conf., Purdue Univ., Lafayette, Ind., 1954, Mimeogr.*, 19 pp.

Buckman, H.O. and Brady, N.C., 1969. *The Nature and Properties of Soils.* Macmillan, New York, N.Y., 653 pp.

Englehorn, A.J., Lawton, K., Meldrum, H.R. and Norman, A.G., 1947. *J. Am. Soc. Agron.*,39: 89–92.

Garren, K.H., 1943. *Bot. Rev.*, 9: 617–654.

Giddens, J., Arsjad, S. and Rogers, T.H., 1965. *Agron. J.*, 57: 466–469.

Gottlieb, S. and Hendricks, S.B., 1946. *Soil Sci. Soc. Am., Proc.*, 10: 117–125.

Greenland, D.J. and Nye, P.H., 1960. *Int. Congr. Soil Sci., 7th, Madison, Wisc., 1960, Comm., III:* 478–485.

Hardy, F., 1944. *Trop. Agric.*, 21: 203–209.

Heyward, F. and Barnette, R.M., 1934. *Univ. Fla. Agric. Exper. Stn., Tech. Bull.*, 265: 1–39.

Heyward, F. and Barnette, R.M., 1936. *Univ. Fla. Agric. Exper. Stn., Bull.*, 302: 1–27.

Howard, A., 1940. *An Agricultural Testament.* Oxford Univ. Press, London, 253 pp.

Jenny, H., 1930. *Mo. Agric. Exper. Stn., Res. Bull.*, 152: 1–66.

King, F.H., 1911. *Farmers of Forty Centuries.* Democrat, Madison, Wisc., 438 pp.

Klemmedson, J.O., Schultz, H., Jenny, H. and Biswell, H.H., 1962. *Soil Sci. Soc. Am., Proc.*, 26: 200–202.

Kuo, M.H. and Bartholomew, W.V., 1966. In: *The Use of Isotopes in Soil Organic Matter Studies.* Pergamon, New York, N.Y. pp. 329–335.

Lambert, E.B., 1941. *U.S. Dep. Agric. Circ.*, 609: 1–15.

Mannering, J.V. and Meyer, L.D., 1961. *Soil Sci Soc. Am., Proc.*, 25: 506–510.

McKenzie, W.M., 1958. *Aust. J. Agric. Res.*, 9: 664–679.

Olsen, R.J., Hensler, R.F. and Attoe, O.J., 1970. *Soil Sci. Soc. Am., Proc.*, 34: 222–225.

Peevy, W.J. and Norman, A.G., 1948. *Soil Sci.*, 65: 209–226.

Pinck, L.A., Allison, F.E. and Gaddy, V.L., 1946. *J. Am. Soc. Agron.*, 38: 421–431.

Pinck, L.A., Allison, F.E. and Sherman, M.S., 1950. *Soil Sci.*, 69: 391–401.

Pratt, P.F., Goulben, B. and Harding, R.B., 1957. *Soil Sci. Soc. Am., Proc.*, 21: 215–219.

Prince, A.L., Toth, S.J., Blair, A.W. and Bear, F.E., 1941. *Soil Sci.*, 52: 247–261.

Russell, E.W., 1961. *Soil Conditions and Plant Growth.* Longmans Green, London, 9th ed., 688 pp.

Salter, R.M. and Schollenberger, C.J., 1939. *Ohio Agric. Exper. Stn. Bull.*, 605: 1–69.

Siegel, O., 1940. *Bodenkd. Pflanzenernähr.*, 21/22: 455–473.

Sinden, J.W., 1938. *Pa. Agric. Exper. Stn., Bull.*, 365: 1–27.

Smith, R.M., Samuels, G. and Cernuda, C.F., 1951. *Soil Sci.*, 72: 409–428.

Stallings, J.H., 1953. *J. Soil Water Conserv.*, 8: 178–184.

Swaby, R.J. and Ladd, J.N., 1962. *Trans. J. Meet., Comm. IV and V, Int. Soil Sci. Soc., N.Z.*, pp. 197–202.

Swaby, R.J. and Ladd, J.N., 1966. In: *The Use of Isotopes in Soil Organic Matter Studies.* Pergamon, New York, N.Y., pp. 153–159.

Tarrant, R.F., 1956. *Soil Sci. Soc. Am., Proc.*, 20: 408–411.

Thornton, H.G., 1929. *J. Agric. Sci.*, 19: 563–572.

Turin, I.V. and Kononova, M.M., 1962. *Trans. Jt. Meet. Comm. IV and V, Int. Soil Sci. Soc., N.Z.*, pp. 203–217.

Van Arsdall, R.N., 1962. *Univ. Ill. Agric. Exper. Stn., Bull.*, 687: 1–20.

Wadleigh, C.H. 1967. *Soil Conserv.*, 33: 27–30, 40.

Chapter 22

GREEN MANURING AND RELATED PRACTICES

INTRODUCTION

A green manure is defined by the Soil Science Society *(Soil Sci. Soc. Am., Proc.,* 1965, 29:337) as a "plant material incorporated with the soil while green, or soon after maturity, for improving the soil." In the narrow sense the green crop is one that has been grown specifically for the purpose of being incorporated into the soil. In actual practice, however, the term is usually used to include the turning under of almost any plant material other than crop residues, and even residues are not always excluded. Actually, so far as turning under top growths is concerned, there is often little difference in the effects of additions of green or dry plant substances to the soil. This is especially true if the green and dry materials differ only in water content; if they differ in nitrogen and lignin content then the effects are likely to be markedly different.

Most crops that serve as green manures are crops that are grown for only a portion of the season between, or following, other main crops in the rotation. They may be summer catch crops, winter cover crops, shade crops (in hot climates) or just weeds. Likewise, a crop such as sweet clover may be seeded in wheat, and later be turned under. Alfalfa may be grown for hay for two or more years and then be turned under before planting corn. A second crop of red clover may be treated likewise. In the same sense a grass or grass–clover sod, when plowed under, serves as a green manure crop. It is obvious that there is such an overlapping that there can be no sharp line of demarcation between a green manure crop and other crops. However, in the discussion that follows the emphasis will be primarily on catch and cover crops that are grown for comparatively short times between other main crops in the rotation.

PAST TRENDS IN GREEN MANURING

The practice of green manuring dates back practically to the beginnings of a settled type of agriculture where crops were grown more or less continuously on the same areas. In China, as long as 3,000 or more years ago, there are records showing that green crops, mostly legumes, were grown and plowed under directly or as compost for the purpose of manuring rice fields. We do not know how extensive this practice was but in later years, as the population increased, it is doubtful if many crops were used directly in this manner because they were considered more valuable as feed and food sources. However, there is no doubt that all plant parts were efficiently utilized as human or animal food, and inedible parts were either incorporated into the soil or added to the compost pile. Even weeds and green branches of trees and shrubs were used as green manures. Plants that grew in canals, as well as the mud from the canals, were removed and utilized directly or via the compost pile.

In Greece and Rome even before the time of Christ, green manuring seems to have been a fairly common practice. Lupines, beans, clovers and other legumes were grown on the poorer soils and incorporated into the soil while green. There is little evidence that this practice was followed in Egypt where the soil was kept fertile through annual flooding.

In medieval Europe green manuring was not generally practiced, if at all, because the feudal system of agriculture prevented the growth of such crops. Usually one or two grain crops were followed by a year of fallow with all areas available for common grazing between crops. It is also doubtful if the small areas devoted to gardening were ever purposely planted to crops to be turned under while green. In fact, legumes that were so commonly grown earlier in Greece and Rome were not used in the general cropping system. Some beans, lentils, peas and vetch were grown in the gardens but chiefly for food rather than for soil improvement. In limited areas around the Mediterranean, which were not under the feudal system of farming, the practice of green manuring was followed to a limited extent during the Middle Ages.

With the beginning of individual land tenure, and the passing of the open field system of agriculture in Europe, there was a revival of the practice of green manuring, first in Germany and a century later in France and England. By the year 1700 it seems that peas, lupines and horse beans were grown fairly commonly and turned under while still succulent, especially on the less fertile sandy soils of Germany. Green manuring supplemented, or, in some instances, replaced animal manures. Even then the matter of economics was given much consideration. Should the legumes be plowed under or fed to livestock? In fact, one of the main reasons for the revival of green manuring was the need to find a substitute for animal manures that were often becoming increasingly inadequate for the needs of agriculture.

Pieters (1927) pointed out that "green manuring is a more thoroughly established practice in Germany, in China and in Japan than in other countries. In Germany, few sandy land farms are operated without the use of green manures." Lupines and serradella are the chief crops used. In England, crucifers are generally used as catch crops. In China, Japan and India various kinds of vegetable matter are carried to the rice fields. In India, the legumes, *Crotalaria* and *Sesbania,* are commonly used to manure rice; green manure crops are also frequently used in permanent plantings of tea, coffee, and *Hevea.*

When the colonists came to America they were generally familiar with the benefits derived from the turning under of green crops, since they had observed the practice in their homelands. They did not follow these practices to any great extent initially, because their environment in America was very different from that in Europe. In America they were dealing with virgin soils and not with poor sandy ones. As the new soils lost their fertility, the colonists merely moved to new areas. By the beginning of the nineteenth century a few American farmers began to adopt the green manuring system, and its use increased gradually in subsequent years.

Although green manuring was originally confined almost completely to the use of legumes, there has been considerable shift to the use of nonlegumes, especially rye, wheat, oats and buckwheat, during the past one or two centuries. This change has been greatly accelerated with the advent of commercial forms of nitrogen. The importance of securing a new supply of nitrogen from the air has been de-emphasized to a considerable extent, whereas the other beneficial effects of green manuring have become relatively more important.

CROPS GROWN

Almost any crop that will grow satisfactorily in a given climate may be used as a green manure, but as a practical matter, the choice is usually very limited. For a particular purpose it seldom happens that a choice of two or more equally valuable crops is offered. One is usually so much superior to others in a given situation that the grower has no hesitancy in making the choice. An exception to this is the cowpea and soybean crops that have similar growth requirements and growth patterns, and thrive under similar climatic conditions. Likewise, some of the small grains may sometimes be interchangeable.

Among the important points that determine the suitability for use as a green manure, aside from climate, season, and soil, are availability and cost of seed, rate and amount of growth, how well it fits into the cropping system, primary purpose for which it is grown, type of root system, ability to compete with weeds, ease of incorporation of the crop into the soil, probable effect on the subsequent crop, and many others.

These subjects are discussed rather fully by Piper and Pieters (1925), Pieters (1927), McKee (1935), McKee and McNair (1948) and Terman (1949).

Leguminous crops

From an agricultural viewpoint, Piper and Pieters classify leguminous green manure crops as: (1) summer annuals, chiefly soybeans, cowpeas, peanuts, beans, velvet beans, common vetch and field peas; (2) winter annuals, including hairy vetch, common vetch, crimson clover, bur clover, field peas and red clover (in the south); and (3) biennials or perennials, comprising red clover, alsike clover, white clover, alfalfa and sweet clover. Each of these crops is adapted more or less definitely to a limited region.

Pieters mentions numerous other legumes that are grown less commonly in the United States and also several that have proven to be especially suited to conditions in various European countries, China, Japan, India, and the Tropics.

Nonleguminous crops

The chief nonlegume green manure crops grown in the United States are the small grain crops, including rye, wheat, oats, millet and barley. Rye is especially favored as a winter cover crop to be turned under in the early spring. Other plants that are occasionally grown include buckwheat, rape and turnips although they are more likely to be utilized for animal feed than as green manure crops. In Europe, rape, mustard and turnips are grown, as well as the small grain crops. Various weeds, such as ragweed, that germinate in grain fields and often make vigorous growths after the grain harvest, act as effective catch crops and as green manures when the grain stubble and weeds are turned under. The most effective green crop of all is usually grass, or a grass–clover sod, but the turning under of such a crop is not, strictly speaking, a green manure practice.

EFFECTS OF GREEN MANURING

Extensive experience in the use of green manures over many centuries, especially during the last two, has shown that they are usually very beneficial. Occasionally harmful effects may be experienced but these can usually be avoided by following good farm management practices.

The exact reasons for the beneficial effects have long been under discussion. Most emphasis has been placed on nitrogen fixation, humus formation, and improved physical conditions in the soil. Beyond this there has been considerable uncertainty, although it was generally recognized that there are many other possible benefits. Much progress has been made during the past 50 years in defining the benefits with more precision. The main facts, as now generally understood, are presented below.

Nitrogen fixation

In the ancient practice of green manuring it seems that legumes were used almost exclusively. At that time nothing was known about nitrogen fixation but yield increases of crops, planted after turning under a green manure crop, served as a good measure of the effectiveness of a given green manure, regardless of the reasons for the benefits. Under conditions that existed in those days there seems no doubt now that the marked yield increases caused by green manures were due more to the increased nitrogen supply that they obtained from the air than to any other single factor. At that time legumes, such as lupines, beans, peas and clovers, were used as manures almost exclusively on poor sandy soils where the nitrogen supply was very inadequate. Any effect on either soil physical conditions or humus supply would have been relatively unimportant on such soils. On the more fertile soils green manures were not commonly used.

In Table 22.I data, taken from Pieters (1927), give average comparative yields and nitrogen contents of the tops and roots of several leguminous crops grown to near-maturity. This table shows the striking differences in the amount of root growth pro-

TABLE 22.I

COMPARATIVE NITROGEN CONTENTS OF THE TOPS AND ROOTS OF SEVERAL LEGUMES (from PIETERS, 1927)

Legume	*Lb. dry weight of crop*		*Percent nitrogen in*		*Total N in tops plus roots (lb.)*	*Nitrogen fixed* (lb.)*
	tops	*roots*	*tops*	*roots*		
Red clover	2000	1006.6	2.70	2.34	77.55	51.70
Alfalfa	2000	1008.4	2.56	2.03	71.67	47.78
Sweet clover	2000	721.0	2.41	2.04	62.90	41.93
Crimson clover	2000	644.8	2.85	2.29	71.77	47.85
Vetch	2000	418.4	3.34	2.16	75.84	50.56
Cowpeas	2000	337.8	2.70	1.45	58.90	39.27
Velvet bean	2000	304.2	2.34	1.27	50.66	33.77
Soybeans	2000	277.4	2.58	1.91	56.90	37.93
Blue lupines	2000	342.0	2.60	1.40	56.79	37.86
Yellow lupines	2000	255.0	2.57	2.17	56.93	37.95
Field peas	2000	90.0	2.80	2.52	58.27	38.85

*Two-thirds of total.

duced by the various legumes. In general, the perennials and biennials have the most extensive root development and the annuals the least. It should be emphasized that these data are for nearly-mature plants, and such plants invariably have much wider top–root ratios than the same plants had at earlier stages of growth. The percentage of nitrogen in mature legumes, both in the tops and roots, also decreases markedly as growth proceeds but the total nitrogen content continues to increase until near-maturity.

In Table 22.I a column is included showing the quantity of nitrogen fixed from the air by the various legumes per ton of hay produced. These figures are probably good approximations for well-inoculated legumes grown on soils deficient in nitrogen, but otherwise suitable for good plant growth. In this table it is arbitrarily assumed that two-thirds of all of the nitrogen in the plants is obtained from the air and the other third from the soil. According to the table, the nitrogen fixation values were in the range of about 34–52 lb. per ton of hay produced.

The percentage of the total plant nitrogen that comes from the air is much less for plants grown in soils that are well supplied with nitrogen. Instead of two-thirds of the nitrogen coming from the air the percentage may be only one-half or one-third. Legumes usually assimilate all or nearly all of the available nitrogen in the soil before they fix appreciable amounts. Since soils continue to release ammonia and nitrates throughout the growing season, the nitrogen so released tends to reduce nitrogen fixation in proportion to the amount released.

Table 22.I gives data in terms of a ton of hay taken as a unit. Green manures are usually turned under when the plants are in the blossom stage or even earlier, and not at the stage where they are most suitable for hay. This means that the nitrogen fixation per unit area is less, although the legumes will have a considerably higher percentage of

nitrogen when young than when mature. During the growth of the legume the total nitrogen content constantly increases until the plants reach the stage of seed production and then levels off. Most of the nitrogen uptake, whether from the soil or from the air, occurs during the first 50–75% of the growth period. At or near maturity some plants may actually release a very small part of their nitrogen to the soil.

Much research has been done on the association of legumes and nonlegumes in an effort to demonstrate that nonlegumes obtain nitrogen that is fixed by legumes. Occasionally proof of direct transfer of such nitrogen has been obtained but only rarely, and in small amounts. Indirectly, the nonlegumes may benefit to a considerable extent through the sloughing-off of legume nodules and root tissues that release nitrogen to the nonlegumes when they decay. The nonlegume may, by removing soil nitrogen, also increase the percentage of the nitrogen in the legume that comes from the air, although the competition will decrease the total weight of the legume produced per unit area (see Chapter 10).

The pounds of nitrogen fixed per acre per crop or season has often been estimated, although not with great accuracy because of the interference of available soil nitrogen. The range of values reported varies widely. Nutman (1965) gives values as follows: alfalfa 50–350; clovers, 50–200; peas, 30–140; pastures with legumes, 10–550. Most commonly-used leguminous green manure crops can be expected to add 25–100, and occasionally 150 lb. per acre per year of atmospheric nitrogen to the soil when they are turned under. There are obviously so many factors involved that any figure given is an uncertain estimate, that can vary two- or three-fold on the same soil from season to season. Over the years this new supply of nitrogen, contributed by leguminous crops, has been a tremendous factor in crop production. It is a much less important factor now when abundant supplies of commercially fixed nitrogen are available.

Organic matter replenishment

When one reads the literature on green manuring published during the first third of the present century, he is likely to be surprised at the importance sometimes placed on this practice as a means of maintaining, or sometimes of increasing, soil organic matter. Primary emphasis was often placed on the amount of plant material turned under, because the larger the green crop the greater the effect on total build-up of humus.

Pieters (1927), for example, states that "it is to be expected that green manuring will increase the organic matter in soils." Again, he states that "the fact that turning under green crops increases the organic matter of the soil is abundantly attested by practical observation." The increase is likely to be temporary and probably not detectable after decomposition has proceeded for a few weeks.

Pieters and McKee (1938) also state that "no very large addition to the soil organic matter can be expected from turning under a single green-manure crop." In another paragraph they admit that "under some conditions, as on sandy soil in a hot climate, this loss (through decomposition) may be so excessive that no permanent addition to the soil organic matter is made even by turning under a heavy green-manure crop." Presumably under average, less extreme, conditions there could be some build-up of organic matter.

It is now well-established that green manures have a negligible effect on total soil organic matter levels if cultivation is continuous, although they do replenish the supply of active, rapidly-decomposing, organic matter. Jenny (1930a,b) was one of the first to call attention to the fact that the organic matter content of soils under constant conditions is determined primarily by climatic conditions, or as Joffe (1955) calls it, the zonality principle. Temperature, rainfall, vegetation, and soil texture and composition are the main determining factors under virgin conditions. When virgin soils are plowed and maintained in cultivated crops then the organic matter level gradually decreases over a period of many years and a new level is established. This lower level can be raised if cultivated crops are replaced by sod crops. It can also be raised by very large additions of outside sources of organic matter, such as animal manures, but this higher level can be maintained only so long as such massive additions continue to be made. Any minor changes in organic matter level brought about by green manures are as likely to be on the negative side as on the positive, depending on the initial equilibrium status of the organic matter. Green manuring involves disturbance of the soil, and the accelerated oxidation counteracts any possible increase in soil organic matter that might be brought about by the added plant material. Whether with or without green manures, we are dealing with a system of yearly cultivation that leads to the lowered level of soil organic matter.

A discussion of green manures, presumably by the editor of *Soils and Fertilizers* (Anonymous, 1949), arrives at a similar conclusion. This states that "to produce a significant increase in the humus content by the addition of organic matter would require the addition of hundreds of tons of organic matter per acre at frequent intervals. The amounts usually applied are entirely inadequate for this purpose, and in warmer climates at any rate are so rapidly burnt out that the soil is enriched only in the salts left behind."

In discussing the constancy of organic matter in soils as dictated by the zonality principle, Joffe even states that "this constant cannot be lowered, no matter what svstem of soil management is followed." In a general way this statement is probably true, but who knows what the minimum is? In actual farming practice we are always dealing with a level somewhat above the possible minimum.

In recent years since the publication of the paper by Broadbent and Norman (1947), considerable research has been conducted to determine the extent to which the addition of readily available sources of energy to soils will accelerate the decomposition of the native soil organic matter. Such experiments usually involve the use of tracer techniques. The magnitude of the effect on the native carbon commonly varies from a negligible to perhaps 100% increase in carbon dioxide release from soils during the first week, often followed by a negative effect a few days later. The overall effect during a growing season is small; in fact, the phenomenon is of more scientific than practical interest (Pinck and Allison, 1951; Stotzky and Mortensen, 1958; Jenkinson, 1966; Sauerbeck 1966; Smith, 1966). Arsjad and Giddens (1966) and Smith (1966) call attention to the fact that when dry soils are moistened there is an increase in decomposition of native soil organic matter, and this increase is sometimes confused with any effect produced by added green manures.

Smith added 1% ^{14}C-labeled soybean, wheat and corn plant tops or roots to a soil containing 3.5% carbon and incubated it for 1 or 2 months. The evolved CO_2 was collected and the ^{14}C measured. Contrary to the findings of Broadbent and Norman, Smith found that "in no experiment did the addition of plant material significantly accelerate decomposition of the indigenous soil organic matter. Among the 53 cases reported, there were 8 where an indication of accelerated soil organic matter loss was observed. However, none of these cases was significantly different from the soil control. On the other hand, in 22 of the reported cases there was a significant reduction in soil organic matter decomposition with the addition of plant parts of wheat and corn." The protective effect as shown by corn roots and wheat roots was reduced but not eliminated by additions of fertilizer nitrogen, which shows that C/N ratio was not a major factor.

In this connection it is pertinent to mention that Löhnis (1926) concluded that "if green manures are incorporated into a soil not too poor in humus a general acceleration of the activities of the microorganisms living in the soil takes place with the result that the nitrification of the green manure nitrogen is accompanied by an intensified mineralization of the humus nitrogen." He reported that occasionally more than 200% of the nitrogen applied was recovered within a few years. The writer was fortunate to be able to obtain Löhnis' original notebook and found that he had made a few errors in calculation that modify his conclusions. In one soil the highest recovery of green manure nitrogen by ten successive crops in the greenhouse was only 73% and the average was 44%. In the other soil the only cases in which recoveries of nitrogen by successive crops were greater than 100% were where the smallest additions of green manures were made. The average recovery for all rates of addition to this soil was 54% for seven successive crops. Where the smallest additions were made, recoveries of more than 100% of the added nitrogen were observed in only four of eleven tests. Even with the highest recovery, 174%, the excess over 100% amounted to only 48 mg out of a total of 1,610 mg, or 3% in seven crops. The results with this soil were so erratic that the few increases could well have been within experimental error. In the light of the new look at the data, this oft-quoted reference should no longer be offered in support of the idea that additions of green manures accelerate the rate of oxidation of native soil organic matter; in fact, the reference can justly be given in support of the opposite view.

Using the ^{14}C-tracer technique Bartholomew and MacDonald (1966) determined that when plants were grown to near-maturity in soil and the tops and roots were removed, the organic debris remaining in the soil amounted to 7–11 lb. for every 100 lb. of total dry weight of the plants, or from 20 to 49 lb. for every 100 lb. dry weight of the roots. This residual debris consisted of fine roots, sloughed-off root materials, and microbial cells, chiefly rhizosphere microorganisms, that utilized root material as it was being released by the growing plants. There was no evidence that the presence of a crop stimulated the decomposition of native soil organic matter.

Green manures can often be used profitably to meet a real need for organic matter in sandy soils that are used annually for the growth of cultivated crops, and where a supply of animal manure is not available. This is the situation that exists, for example, in the coastal plain sandy loam soils of south New Jersey that are used annually for the production of truck crops. The problem here involves both the physical conditions of the soil and its limited ability to retain and supply available nutrients to the vegetable crops. Since these soils are commonly plowed early each spring and cultivated repeatedly during the summer, the organic matter disappears rapidly. To meet the need for active organic matter many growers now sow ryegrass, either alone or in combination with vetch or crimson clover, as a winter cover. Others may grow a midsummer catch crop of soybeans, cowpeas or Sudangrass.

App et al. (1956) summarize studies with market-garden soils conducted at Seabrook, New Jersey, with ryegrass, wheat, rye and barley, grown alone or with crimson clover, and fertilized with 0, 60 and 120 lb. per acre of nitrogen. These crops are turned under in March or April. In one year wheat that received 120 lb. of nitrogen produced a yield of 12,000 lb. of dry matter per acre and had a nitrogen content of near 2%. All cover crops had a beneficial effect on soil aggregation, but sod crops, such as ryegrass, were most effective. The authors emphasize that the selection, growing practice, and time of plowing under a green manure depend upon the cash crop that follows, and on soil tilth. They state that this cover crop system of farming has markedly increased the yields of cash crops without an increase in the total amount of fertilizer used. This finding may not hold for many other regions and cropping systems, since it has been shown frequently that greater efficiency of nitrogen, as measured by yields, is usually obtained when it is applied directly to the cash crop (Pinck et al., 1948a,b; Ensminger and Pearson, 1950; Morgan and Hanna, 1962; Giddens et al., 1965).

Conservation of nutrients

Green manure crops, whether grown as catch crops or as cover crops, conserve nutrients by minimizing losses in the drainage water. The late summer or fall crop is very effective in this respect since the rate of nitrification roughly parallels the temperature. The cover crop serves the same purpose, but to a lesser extent because nutrient release during the colder months is at a minimum. In fact, it is often desirable to add nitrogen fertilizer in the fall at seeding time to speed up the growth of nonlegume cover crops and provide good early soil protection.

The quick-growing catch and cover crops are also effective in erosion control. They can usually be seeded in the preceding crop, or perhaps by merely discing the soil, or using other minimum tillage procedures. If more extensive disturbance of the soil is made, erosion may proceed to such an extent that the benefits of the green crop are more than counteracted.

Catch crops and cover crops are not always turned under and hence, strictly speaking, are not green manure crops. In fact, turning under these crops while they are green may be inadvisable if a crop is not to be planted soon after. Succulent green crops decompose so rapidly that a considerable portion of the nutrients that they assimilate may be released and lost. In many cases the green crop can be utilized as a feed with no appreciable loss in benefits. One example of this is where rape is grown as a catch crop and hogs allowed to graze on it for a time before plowing. Likewise, a cover crop of small grains may serve as a winter pasture in the southern states, and be turned under in the spring just before planting a main crop. In the latter case it is not uncommon to apply commercial nitrogen in the fall in order to provide more winter feed.

Many of the benefits of catch crops, outlined here, can be realized by merely allowing the crop to be winter killed and remain undisturbed until the usual time for spring plowing. There may be some small amount of leaching of nutrients but most of the other benefits are not greatly affected. This practice certainly provides good soil protection at minimum cost, and provides for nearly full physical benefits from root growth and improvement of tilth. Whether this procedure, which is usually not the best, is followed depends upon the farming system, the climate, soil, topography, and many other factors.

Increase in available nutrients

When a succulent green crop is incorporated into a moist, warm soil, decomposition starts almost immediately and the release of ammonia (if nitrogen content is above 2.0) and other major and minor nutrients begins. This release is usually very rapid during the first one or two months but continues at an ever-decreasing rate during the remainder of the growing season. There will in most cases be little residual effect during the second season. This steady release of nutrients assures ideal growth conditions for the crop that follows except during the first few days when other factors may interfere with growth.

The nutrients released from the decaying green manure include those that would have been lost by leaching if a green manure had not been grown; those made available from the soil through root action and various biochemical processes; carbon dioxide formed from the decaying plant material; and any nitrogen that may have been fixed symbiotically or nonsymbiotically. During the decay process a portion of the minor nutrients undergo chelation, and are thereby kept from leaching and also held in a highly available form for the crop that follows. This constant release of available nutrients more or less as they are needed by the following crop constitutes one of the main benefits derived from the growing of green manure crops. Some of these released nutrients are again made unavailable by chemical and biological action, but the abundant supply of organic matter helps to curtail this reverse action.

Carbon dioxide

Various writers have from time to time emphasized the importance as a plant nutrient of the carbon dioxide released from roots, and by the microorganisms living on the roots (rhizosphere microorganisms) and on the organic matter. The amount of carbon dioxide in the upper air is fairly constant at 0.03% by volume. However, where a crop is grown that produces rather heavy vegetation the percentage in the air at the soil surface may be in the range of 0.05–0.28% (Miller, 1938) even where no green manures have been added. The carbon dioxide content of soil air is even higher, and figures reported cover the range of about 0.1 to occasionally as high as 5% by volume of air. The higher percentages are usually found where large amounts of readily decomposable organic matter are present in poorly-aerated soils.

Many experiments have shown that crop yields are larger where the carbon dioxide is above the normal level in air provided that it is not too high. There have been reports that the growth of some kinds of plants has been inhibited by concentrations as low as 1.0–2.0% but this may have occurred where oxygen was inadequate (Bergman, 1959). The writer has grown the blue-green alga, *Nostoc muscorum,* for periods of several months in air enriched with 5% carbon dioxide with excellent results (Allison et al., 1937). This organism could scarcely be considered as a hardy type, and insensitive to unfavorable growth conditions.

The ability of plants to utilize the carbon dioxide of the soil air directly through the roots has been a subject of much interest and study. Numerous experiments have demonstrated that plant roots can take up carbon dioxide from the soil solution but the amount is not large. One group of investigators has estimated that the amount so absorbed may be as high as one-fourth that taken up by the leaves, but most others have obtained values in the range of near zero to 5%. This carbon dioxide is transported to the leaves and there utilized in photosynthesis just as is the carbon dioxide of the air.

The carbon dioxide liberated during the decomposition of green manure crops undoubtedly does have a beneficial effect on the growth of any crop present but the evidence indicates that the effect is not large. There may be some increase in the solubility of soil minerals, but the increase in photosynthesis produced by the released carbon dioxide is probably small. If a heavy, compact crop were present to trap much of the released gas near the soil surface the benefits might be large, but in actual practice such a crop is not present for several weeks after the green crop is turned under. By that time the rate of carbon dioxide release from the treated soil may be only slightly greater than from a similar untreated soil.

Root effects

A very important benefit to be derived from green manure crops is that effected through their root systems. This is especially true for the very deep-rooted legumes, such as alfalfa, sweet clover, lupines and kudzu. Other crops, such as red clover, soybeans, cowpeas, and even the small grains, also often root rather deeply. When these are grown on heavy, but well-drained, soils the roots may penetrate to a depth of two or more feet and often below the root zone of most of the crops commonly grown in the rotation. They are sometimes able to penetrate a layer of hardpan, or near hardpan. On dense soils legumes are usually more effective than nonlegumes, both because of their ability to penetrate and because a larger part of the plant consists of roots. These deep roots remain in the soil to decay and furnish nutrients to crops that follow. Very commonly the roots of the crop that follows grow along the old root channels, and when they do they have available a supply of water that otherwise they could not utilize.

Another very important benefit realized from the roots of green manure crops is the big effect on the aggregation of the finer-textured soils. Crops with very finely divided and extensive, but not necessarily deep, root systems are most effective. Small grain crops meet this requirement and are most used for this purpose (Benoit et al., 1962). A single heavy cover crop of rye, planted in the early fall, has been known to produce a very marked improvement of the soil. The chief factors and mechanisms involved in aggregate formation and stabilization, and the role that root systems play in the process, are discussed in Chapter 16.

Tilth and moisture relationships

When green manures are incorporated into a soil and have been thoroughly decomposed there is an improvement in tilth of the finer-textured soils. This is brought about by the interplay of a number of factors that result in improved aggregation of the fine clay particles and in a lower bulk density. Both living organic matter (growing roots) and dead organic matter (polysaccharides and low-weight humic substances) play the key-roles in providing the good tilth. Organic matter also improves sandy soils, but here the effect is largely due to the increased moisture holding capacity and to the higher level of available nutrients.

When heavy green manure crops are plowed under, the natural movement of moisture from the main body of soil to the surface is largely prevented for a time until the organic matter has undergone considerable decomposition, and capillarity has been restored. The fresh plant material breaks the capillarity and during periods of hot dry weather the upper layer of soil may lose most of its moisture. Obviously under such conditions the soil is not a suitable medium for plant growth, and it is largely for this reason that seeding of crops should be postponed for at least two weeks until a suitable seedbed can be prepared, and moisture conditions are more nearly normal. After this initial period the beneficial effects of active organic matter are in evidence. A uniform mixing of the organic matter with the soil is advantageous, but difficult to bring about for practical reasons.

The role of organic matter in water infiltration and retention, in drainage, and in water-use efficiency is discussed in Chapter 17. These beneficial effects are attributable in large part directly to the independent action of organic matter, including its diluting effect. In addition, is the effect that it has on aggregation of soil particles and on its interaction with inorganic matter to form organic–inorganic colloidal materials. Since green manure crops are readily decomposed, the improvement in tilth and in moisture relationships is realized comparatively rapidly after their incorporation into the soil.

In semi-arid regions (rainfall less than about 20 inches) where moisture is commonly the limiting factor in crop production, and the main factor governing the choice of crop and cultural practices, green manures are seldom used. Under conditions where there is inadequate moisture for the main crop, and where bare fallows are often maintained for moisture conservation, it is obvious that there is no place for green manures unless irrigation water is available (Army and Hide, 1959). Fortunately, there is much less need for catch and cover crops in these regions where erosion and leaching are at a minimum, where soil physical conditions are usually reasonably satisfactory, and where low crop yields minimize the problem of providing an adequate supply of available nutrients.

Erosion control

In hilly regions where gully formation on clay and loam soils is a common, or possible, occurrence there is often a need for catch and cover crops if these can be fitted in between main crops with very little disturbance of the soil. Of course sod crops are preferable for such soils but they may be impractical for the type of agriculture common to the region. The primary need here is to keep the soil covered with some kind of vegetation as near continuously as possible, and if a green manure crop aids in doing this, then it probably should be used.

Considerable emphasis has been given to the good effects of shade produced by a dense growth of a green manure crop. Such a crop eliminates the damage to soil aggregation produced by raindrop splash, and thereby reduces the tendency toward crust formation. Aside from the improved physical condition of the soil, it is common for the dense vegetation to keep the soil surface moist and thus more favorable for biological activities. Increased moisture and a cooler soil also lead to more root growth near the surface both of green manure crop and of any companion crop that may be present, as where a cover crop is grown in orchards or between rows of other crops. In hot climates, both green manure crops and others are often grown primarily to serve as shade for other crops, but in more northern regions they are seldom grown specifically for shade apart from the other benefits mentioned.

Control of plant diseases

The addition of green manures to soils has been shown to effect control or partial control of a number of plant diseases. These include potato scab, take-all disease of wheat, and root rot of cotton and of snap beans. This method is not always successful and many factors, which are not well understood, affect the results. This subject is discussed in Chapter 19.

Harmful chemical and biological effects

Harmful effects are sometimes noted when crops are planted too soon after the incorporation of a green crop into soil. The break in capillarity of the soil column, followed by the drying out of the surface layer and the production of a featherbed type of seedbed have already been mentioned. In addition, other bad effects on newly planted seedlings have been observed that have been attributed by various workers to: (1) excess carbon dioxide; (2) organic phytotoxic substances; (3) excess ammonia and nitrites; and (4) damping-off fungi.

One of the earliest explanations offered for the harmful effects was high concentration of carbon dioxide in the immediate vicinity of the decomposing green manure. This is a possibility, since we are concerned with seedlings, and since we know that occasionally the carbon dioxide partial pressure in the soil air may be as high as 5% and possibly higher. There is now less emphasis on this explanation, since others seem to be much more important.

The formation of toxic organic substances, discussed in Chapter 18, is also a distinct possibility. Such substances are formed by higher plants and also by microorganisms that are active in their decomposition. Many soil organisms are known to produce antibiotics that are toxic to some plants, but there is no evidence at present that such antibiotics are produced in soils in sufficient concentrations to be appreciably toxic. It is fortunate that any harmful products that may be derived from green manures are usually destroyed within two or three weeks, and most antibiotics are adsorbed by the soil colloids.

When succulent plant materials that have narrow carbon–nitrogen ratios are mixed with soil there is an abundant evolution of ammonia that may either become ionized or remain unionized, depending on the pH. Since the ammonia itself raises the pH to perhaps 8 or higher, most of the ammonia initially is unionized but as it undergoes chemical reactions, absorption, and biological nitrification the pH usually soon drops to 7 or lower. During the initial period the content of unionized ammonia may be sufficiently high to cause injury to seedlings. Furthermore, the ammonia can, and frequently does, act to inhibit oxidation of nitrites to nitrates, although oxidation of ammonia to nitrites proceeds normally. The result is that nitrites tend to accumulate for a period of a few days, and may occasionally reach concentrations as high as 50–100 p.p.m. Such concentrations are very toxic to most plants, and especially to seedlings. Sometimes this accumulation may be further favored by the absence of a vigorous nitrifying flora. The comparatively short duration of very large concentrations is attributable to the ability of the nitrite to react with soil organic matter. At pH values below 6 nitrites are unstable and may release molecular nitrogen. Since the initial pH tends to be high, where nitrites are stable, it is likely that most of them react with organic matter before the pH is low enough for much decomposition to nitrogen gas to occur. Our knowledge of the importance of nitrite toxicity to seedlings is meager, but recent evidence indicates that it may be an important factor in connection with green manures.

Damping-off fungi, and possibly other types of microorganisms, have been shown frequently to be responsible for marked injury to germinating seedlings that are attempting to grow too soon after turning under a green manure crop. Cottonseed and soybeans seem to be unusually susceptible, probably due in large part to the abundant supply of readily available energy-yielding substances in the seeds (Fred, 1916). The fungi find food conditions ideal and the temperature suitable for rapid growth, and often cause extremely severe damage to the seedlings. These fungi do not, however, limit their attack to cotton but their activities are widely distributed over various types of seedlings; starchy seeds are most resistant.

FINAL REMARKS

The above discussion has shown that nearly all of the effects of green manures are beneficial and fortunately, the harmful effects can be avoided at minimum costs by following good farm management practices. The decision, therefore, as to the desirability of growing such crops, and what crops, is largely an individual one and depends upon a large number of factors that are too obvious to need listing here. Often the determining factor is likely to be economics, which also varies from farm to farm, and is dependent upon the need for green manuring crops and the use to be made of them. Rarely will it be profitable to substitute a green manure crop for another in the rotation, but it is obvious that it would be profitable to make greater use of fill-in catch and cover crops than is now being done. This applies particularly to the warmer soils where the need for them is greatest. The suitability of various green manure crops for use in the many different cropping systems in the United States is discussed rather fully by Pieters (1927).

REFERENCES

Allison, F.E., Hoover, S.R. and Morris, H.J., 1937. *Bot. Gaz.*, 98: 433–463.

Anonymous, 1949. *Soils Fert.*, 12: 155–159.

App. F., Ichisaka, V. and Gill, T.S., 1956. *Better Crops with Plant Food*, 40: 9–16, 40–46.

Army, T.J. and Hide, J.C., 1959. *Agron. J.*, 51: 196–198.

Arsjad, S. and Giddens, J., 1966. *Soil Sci. Soc. Am., Proc.*, 30: 457–460.

Bartholomew, W.V. and MacDonald, I., 1966. In: *The Use of Isotopes in Soil Organic Matter Studies.* Pergamon, New York, N.Y., pp. 235–242.

Benoit, R.E., Willits, N.A. and Hanna, W.J., 1962. *Agron. J.*, 54: 419–420.

Bergman, H.F., 1959. *Bot. Rev.*, 25: 417–485.

Broadbent, F.E. and Norman, A.G., 1947. *Soil Sci. Soc. Am., Proc.*, 11: 264–267.

Ensminger, L.E. and Pearson, R.W., 1950. *Adv. Agron.*, 2: 81–111.

Fred, E.B., 1916. *J. Agric. Res.*, 5: 1161–1176.

Giddens, J., Arsjad, S. and Rogers, T.H., 1965. *Agron. J.*, 57: 466–469.

Jenkinson, D.S., 1966. In: *The Use of Isotopes in Soil Organic Matter Studies.* Pergamon, New York, N.Y., pp. 199–208.

Jenny, H., 1930a. *Soil Sci.*, 29: 193–206.

Jenny, H., 1930b. *Mo. Agric. Exper. Stn., Res. Bull.*, 152: 1–66.

Joffe, J.S., 1955. *Adv. Agron.*, 7: 141–187.

Löhnis, F., 1926. *Soil Sci.*, 22: 253–290.

McKee, R., 1935. *U.S. Dep. Agric., Farm Bull.*, 1750: 1–16.

McKee, R. and McNair, A.D., 1948. *U.S. Dep. Agric., Farm Bull.*, 1663: 1–20.

Miller, E.C., 1938. *Plant Physiology.* McGraw-Hill, New York, N.Y., 2nd ed., 1201 pp.

Morgan, G.W. and Hanna, W.J., 1962. *Agron. J.*, 54: 396–399.

Nutman, P.S., 1965. In: W.V. Bartholomew and F.E. Clark (Editors), *Soil Nitrogen. Agronomy*, 10: 360–383.

Pieters, A.J., 1927. *Green Manuring – Principles and Practice.* Wiley, New York, N.Y., 356 pp.

Pieters, A.J. and McKee, R., 1938. In: *Soils and Men. – The Yearbook of Agriculture, 1938.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., pp. 431–444.

Pinck, L.A. and Allison, F.E., 1951. *Soil Sci.,* 71: 67–75.

Pinck, L.A., Allison, F.E. and Gaddy, V.L., 1948a. *Soil Sci.*, 66: 39–52.

Pinck, L.A., Allison, F.E. and Gaddy, V.L., 1948b. *J. Am. Soc. Agron.*, 40: 237–248.

Piper, C.V. and Pieters, A.J., 1925. *U.S. Dep. Agric., Farm Bull.,* 1250: 1–45.

Sauerbeck, D., 1966. In: *The Use of Isotopes in Soil Organic Matter Studies.* Pergamon, New York, N.Y., pp.209–221.

Smith, J.H., 1966. In: *The Use of Isotopes in Soil Organic Matter Studies.* Pergamon, New York, N.Y. pp.223–233.

Stotzky, G and Mortensen, J.L., 1958. *Soil Sci. Soc. Am., Proc.,* 22: 521–524.

Terman, G.L., 1949. *Maine Agric. Exper. Stn., Bull.,* 474: 1–40.

Chapter 23

NITROGEN UTILIZATION IN CROP PRODUCTION

INTRODUCTION

About 5% of soil organic matter or humus consists, on the average, of nitrogen combined with the other elements that are essential for crop growth. Nitrogen is usually the element that is of primary importance in the determination of crop yields and quality. It is required in comparatively large amounts and is likely to be deficient in soils unless the best farm management practices are used.

Nitrogen is a transient element, as brought out in other chapters of this book, and an understanding of the factors that affect it is highly important in attempting to secure maximum efficiency in its use. Since inadequate nitrogen leads to low yields and poor quality, whereas too much can occasionally be harmful, the proper management of this element often presents problems. Some of the main factors involved are discussed here and also by Allison (1957). Since nitrogen can move back and forth readily between organic and inorganic forms, the present discussion will deal with both sources of the element including added fertilizer nitrogen.

FUNCTIONS OF NITROGEN IN PLANT GROWTH

Nitrogen is the one element above all others that we associate with growth. As pointed out in Chapter 14, it is a constituent of proteins, enzymes, chlorophyll, deoxyribonucleic acids that make up the genetic code, amino acids and many intermediates involved in the synthesis of plant substances. It is characteristically present in comparatively large amounts in the growing tips of plants, but it can move about readily from one part of the plant to another to meet the primary needs at the time.

Since nitrogen is a constituent of chlorophyll, the appearance of the leaves is a rough measure of the amount present. A very deep green, healthy appearance is an indication of an abundant nitrogen supply. On the other hand, a very light green color, usually associated with stunted growth and possibly dying older leaves, constitutes a strong indication of nitrogen deficiency, even though occasionally similar symptoms can be due to deficiencies of other elements, or to unfavorable growth conditions. With subnormal amounts of chlorophyll present photosynthesis is greatly reduced and yields are markedly curtailed.

The presence of too much available nitrogen can result in a very succulent plant of excessive height and low sugar content. Tall plants and heavy grain yields may sometimes result in lodging and difficulty in harvesting. Occasionally abundant nitrogen results in delayed maturity, but recent studies show that usually the reverse is true for most crops, except perhaps where the application is excessive. Under extreme conditions, nitrate nitrogen may accumulate in forage crops to such an extent as to be toxic to animals.

SOURCES OF NITROGEN

The original source of all nitrogen that enters into life processes was long considered to be the atmosphere. Stevenson (1957) has, however, presented evidence that perhaps 20 times as much nitrogen is held as ammonium within the lattice structures of silicate minerals as is present as elemental nitrogen in the atmosphere (see Chapter 11). Only a negligible amount of the ammonium of rocks is utilizable by plants, and hence the agriculturalist must depend upon other sources of nitrogen. These are: (1) soil nitrogen that originally came almost exclusively from the air; (2) nitrogen constantly being fixed from the air by microorganisms and in a minor way by electric discharges in the air; and (3) nitrogen of commercial fertilizers derived chiefly from the air by industrial processes.

Soil nitrogen

Until quite recent times, and even today in many localities, organic matter was, or is, the chief and often the only important source of nitrogen for crop production. This supply of nitrogen was often so large in soils first brought under cultivation that there was no need for supplemental nitrogen. As crop yields decreased, animal manures and other outside sources of nitrogen were given increasing attention.

In the present age of abundant fertilizers, soil nitrogen is still important but in a somewhat different sense than formerly. The soil is no longer serving as a mine but more as a reservoir to which nitrogen is both added and removed. As a result of biological immobilization and mineralization, mineral nitrogen may at one time be decreased and at other times be increased. Ideally, the aim is always to have adequate available nitrogen present to meet the needs of the crop but to avoid excesses that may be subject to loss via leaching or as gases. Of course this ideal can seldom be realized, but nevertheless the soil organic matter does go a long way toward the attainment of this goal. The higher the level of organic matter in soil, the easier it is to attain this ideal.

Biological nitrogen fixation

The chief channel by which atmospheric nitrogen is added naturally to soils and to plants is via symbiotic bacteria living chiefly, but not exclusively, on legume roots. A few nonlegumes also fix nitrogen symbiotically, but since these plants are chiefly shrubs and trees their importance in general agriculture is minor. Fixation of nitrogen by free-living bacteria has undoubtedly been a major factor in the building up of soil nitrogen in undisturbed soils over the centuries, but is of minor importance in any one year in cultivated soils. Nitrogen-fixing blue-green algae are important contributors to the nitrogen supply in some rice paddies, and possibly in some permanent grasslands, but are not important in cultivated soils (see Chapter 10).

The importance of crop rotation, and of the inclusion of a legume in the rotation, has long been emphasized for numerous reasons which need not be listed here in detail. In the past the legume was included for the primary reason that its growth is not dependent upon soil nitrogen. When properly inoculated, and the soil conditions are favorable, legumes make excellent growths on very nitrogen-deficient soils. Under many conditions a considerable portion of this newly-fixed nitrogen is left in the soil or is returned to it in the form of crop residues or manures. Many legumes with deep roots are of considerable benefit in opening up impermeable subsoils. They were also prized as animal feeds, and the extent to which they were grown was often dependent upon whether they were needed for this purpose. It was seldom profitable to grow them in the rotation solely for the nitrogen that they supplied; at least this was not the most economic practice.

The longtime emphasis placed on the value of crop rotations, including legumes, led to considerable controversy during the past two or three decades since abundant supplies of fertilizer nitrogen became available. It was generally agreed that nitrogen could usually be purchased in the bag at less cost than it could be obtained by growing legumes in the main rotations. But was such a practice advisable? We now know that the answer to this question is usually yes if the legume is being grown primarily for its contribution of nitrogen, and if the nonlegume crops are properly selected. In fact, the availability of abundant commercial nitrogen has had the effect of greatly reducing the emphasis on the need for any rotation of crops except perhaps on certain problem soils or where diseases are a major factor. Corn, for example, when heavily fertilized, produces such an abundant supply of roots and residues year after year that the residual effect on the soil is usually as satisfactory as where a rotation is used that includes legumes. There is no intention here to discredit the use of legumes, but merely to emphasize that they are now less essential so far as the maintenance of soil fertility is concerned than they were prior to the fertilizer era.

Legume-grass pastures have proven to be very satisfactory under many soil and climatic conditions, notably in Australia and New Zealand where annual fixations of 150–300 lb. per acre are not uncommon, and occasionally are reported to be as high as 600 lb. per acre (Walker et al., 1954; Walker, 1956). In these mixtures the grass commonly assimilates most of the inorganic nitrogen as it is released from soil organic matter, thereby leading to high fixation values for the legume (Whitehead, 1970). As has been shown repeatedly, the presence of inorganic nitrogen reduces fixation more or less in proportion to the amount present. Under a pasture system of farming the constant removal of the nitrogenous herbage, if properly regulated, results in high fixation of nitrogen at comparatively low cost. Under such conditions, where land and labor charges are low, it is obvious that commercially-fixed nitrogen cannot compete satisfactorily with nature's method.

Commercial nitrogen

Abundant supplies of nitrogen are now available at reasonable prices in various reduced and oxidized forms. These include urea, ammonium salts, anhydrous ammonia, Cyanamid, urea–ammonium nitrate solutions and various nitrate salts. The organic materials that were so important in fertilizer mixtures at the beginning of this century have essentially disappeared from the market. Because of the increasing interest in the disposal of city wastes, it is expected that in the future there will be an increase in the use of processed sewage and garbage. These materials, when properly prepared, are good sources of nitrogen and are somewhat less readily available than are most of the nitrogen compounds now in common use. Urea formaldehyde products, and other slowly available materials, are used to a limited extent for special purposes. These materials are satisfactory sources of nitrogen, but are not of equal value under all conditions, and for all crops. All of these materials, when added to soil, are transformed into ammonia and nitrates and this tends to minimize the differences in their effects on plants.

The trend in the use of fertilizer nitrogen in recent years in the United States is shown in Fig. 23.1, supplied through the courtesy of L.B. Nelson of the Tennessee Valley

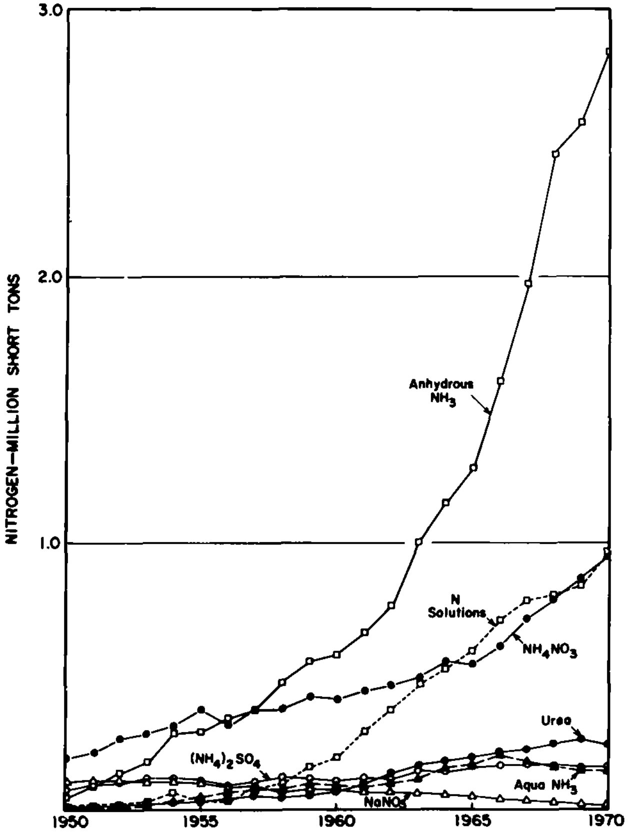

Fig.23.1. Consumption of major nitrogen fertilizers and materials in the United States, 1950–1970. (From L.B. Nelson, personal correspondence, 1971.)

Authority (also see Nelson, 1965, for discussion of these data). There has been a rapid increase in the use of anhydrous ammonia and a moderate increase in the consumption of ammonium nitrate and nitrogen solutions. These three nitrogen sources represent the bulk of the nitrogen used. The older sources, such as ammonium sulfate and sodium nitrate, have now become comparatively minor nitrogen sources.

According to Nelson and Hauck (1965) the average rate of application of nitrogen fertilizer materials is only about 13 lb. of nitrogen per acre of arable land in the United States. When one considers that it requires about 200 lb. of nitrogen to produce 100 bushels of corn, it is obvious that the soil is still the main nitrogen source for many crops in many localities. Nelson and Hauck state that in 1959 no nitrogen was applied to 39% of the corn acreage, 80% of the sorghum, 27% of the cotton, 67% of the wheat and 92% of the hay and cropland pasture in the United States. In some of the European countries the rate of nitrogen use is considerably higher, but in the underdeveloped countries of the world the rate used is only a small fraction of that in the United States.

ASSIMILATION OF NITROGEN BY PLANTS

Most plants can utilize directly ammonia, nitrates and a few organic compounds such as urea, amino acids and amides. In addition, nitrite is usually assimilated readily, but at soil concentrations greater than about 10–20 p.p.m. is likely to produce signs of toxicity.

Most plants absorb NH_4^+, K^+, NO_3^- and Cl^- rapidly, whereas Ca^{2+}, Mg^{2+} and SO_4^{2-} are taken up slowly. This difference in rate of ion uptake can under some conditions have considerable effect on pH and on growth. If a complete culture solution contains nitrogen only as NO_3^- its rate of uptake is more rapid than that of the cations with resulting rise in pH of the culture solution and a substitution of HCO_3^- for NO_3^-. Where all the N in a nutrient solution is present as NH_4^+ it is taken up rapidly and as H^+ is substituted for the NH_4^+ the pH of the solution falls. Concurrently the organic anion content of the plant material changes and the pH of the plant juice remains around 6.

Ionic balance in plants is a subject that deserves much consideration when the relative merits of ammonium and nitrate are being considered. This can be studied satisfactorily only in solution or sand cultures where nitrification is absent, and where there is no soil present to affect the pH. The total cation content (C) with which we are concerned includes $K^+ + Na^+ + Ca^{2+} + Mg^{2+}$, and the total inorganic anion content (A) is $NO_3^- + H_2PO_4^- + SO_4^{2-} + Cl^-$. The organic nitrogen and sulfur are present in reduced forms. According to De Wit et al. (1963) when NO_3^- and SO_4^{2-} are reduced the negative charge is released as HCO_3^- which may either be changed into an organic anion, be exchanged with an inorganic anion, or be neutralized by H^+ uptake. Utilization of phosphate does not change its ionic state.

De Wit et al. (1963) state that the difference between the cation and inorganic anion contents (C-A) is numerically equal to the organic anion content. Maximum growth of plants is obtained when the organic anion content is constant per unit of dry weight.

Normal growth is possible at a wide variation of the (C) content, of the (A) content, and of the content of the individual ionic species, if the organic anion content stays normal. This indicated to these workers, and also to Noggle (1966), that the organic anions are essential for good growth; a reduction in these anions reduces growth.

De Wit et al. point out that an excessive cation content may occur where there is a shortage of K^+ in the presence of other cations that are readily taken up. Even though these other ions exert their positive charge, the K ion seems to be the only one that accompanies the excess organic ions as they move downward in the plant. In the case of ammonium fertilization, growth often is slowed down because of competition between $NH_4{}^+$ and other cations and release of H^+ as organic nitrogen is formed.

Many workers have shown that under proper conditions ammonia and nitrates are about equally good sources of nitrogen in solution or sand cultures. Tiedjens and Robbins (1931) observed that tomatoes, soybeans, and peach and apple seedlings utilized ammonia very satisfactorily at pH values of 7–8 or above but not at acid pH values. In contrast, nitrate-N was assimilated most efficiently at pH 4 and 5. Because of the pH effect, plants are more likely to grow better on nitrate than on ammonia. A mixture of the two forms of nitrogen may be even better if the pH varies considerably.

There are, however, many exceptions to the above statements that need to be mentioned. For example, McFee and Stone (1968) in short-term experiments and at comparatively low nitrogen levels, reported that "radiata pine (*Pinus radiata* D. Don) seedlings grown either in soil, solution culture, or exchange resins exhibited greater growth and N uptake with an ammonium source than with nitrate. This was true in experiments at several levels of acidity, in all three growth media and regardless of the root zone temperature or N level maintained." White spruce *(Picea glauca)* seedlings, so far as tested, also gave favorable responses to ammonium–nitrogen. The authors point out that there has not been good agreement in the results of various workers. Important variables besides plant species appear to be age of plants, soil pH, nutrient concentration, temperature, and possibly duration of the tests.

Numerous experiments (Jansson et al.,1955) have demonstrated that ammonia is commonly utilized preferentially by microorganisms and higher plants when growth conditions are ideal. This is not surprising considering that amino acids, proteins and other forms of nitrogen found in plants are present in reduced form. Any nitrates that are taken up by the plant must first undergo reduction to NH-type compounds before they can be utilized. Although some workers have placed considerable emphasis on this fact, it is actually a minor one in nitrogen utilization. In practice the preference for ammonia may be observed for only a few hours, and plants are not much affected by this time differential so long as the nitrogen supply is adequate.

When comparisons of various nitrogen sources, with the exception of nitrites, are made in soil under good growing conditions the plant response is commonly similar because nitrification usually proceeds rapidly and the plant actually assimilates most of its nitrogen in the nitrate form, regardless of the form in which it is added. There are a few exceptions to this statement as, for example, where ammonia is added to a soil of high ammonium-fixing capacity. Also, in very acid soils, or where excessive amounts of ammonia are added, nitrate formation may be retarded and gaseous losses of nitrogen be favored. Acidity, as mentioned above, is an unfavorable environment for ammonia utilization.

FACTORS THAT AFFECT EFFICIENCY OF USE

The efficiency with which nitrogen is utilized in crop production is affected by so many factors that few general unqualified statements can be made regarding its use. Some of the more important factors are discussed below, as well as in other chapters. Extensive discussions of the subject have been published by many authors including Harmsen and Van Schreven (1955), Allison (1964, 1966), Bartholomew and Clark (1965), Nelson and Hauck (1965) and Donald et al. (1963), Parr (1967).

Soil

The physical, chemical and biological properties of soils play a major role in determining the effectiveness of added fertilizer nitrogen. Well-aerated sandy soils serve as an excellent substrate for rapid nitrification of any reduced forms of nitrogen that are present. They are so low in organic and inorganic colloids, however, that any nitrate formed that is not assimilated rapidly by plants is subject to leaching to lower levels, and perhaps to the groundwaters. Since the main habitat of soil microorganisms is the soil organic matter and the rhizosphere, the nitrifying flora may be deficient in very sandy soils, but this is not an important factor. Only rarely are the nitrifying bacteria absent from soils, and their numbers can increase rapidly when reduced forms of nitrogen are added, except where soils are more acid than about pH 4.5–5.0.

Fine-textured soils that are well-aggregated, have good drainage, and have an adequate supply of bases are also good nitrifiers. The nitrate formed is held within the root zone except possibly during periods of exceptionally high rainfall. Many experiments have shown that loss of nitrogen by leaching from such soils is usually almost negligible during the growing season when evaporation and transpiration are high, unless the annual rainfall is greater than about 40–50 inches, and very unevenly distributed (see Chapter 13).

Denitrification can also be an important factor in fine-textured soils where aeration is normally poor, or during periods of high rainfall. It is even possible for nitrification to occur in the better-aerated parts of a soil, and denitrification to take place inside the more anaerobic aggregates or spaces of the same soil. The extent to which this occurs under field conditions is largely an unanswered question.

Ammonium fixation is also a factor that affects the efficiency of nitrogen utilization (see Chapter 11). If the soil is high in 2:1 type minerals much of the ammonium will be fixed and thereafter be nitrified or released to crops only slowly. Under some conditions this may be an advantage, but present information indicates that it is more likely to be a disadvantage. In such soils nitrate may be preferred over reduced forms of nitrogen if quick response is desired.

The texture and structure of a soil also affect plant response to nitrogen additions through effects on root development and depth of penetration. A restricted root system limits the ability of the plant to assimilate nutrients and also limits its uptake of water. Since the movement of water through soils by capillarity is slow and limited, the plant roots must literally go after it. A deep root system, therefore, assures that a much greater proportion of the supply in the soil is available to the plant. In addition, soil compaction limits the absorption of the rainfall. Such unfavorable conditions do of course lower the efficiency of applied nitrogen.

Climatic factors

Temperature affects nitrogen response primarily through its effect on plant growth, and secondarily on the rate at which the chemical and biological processes occur in soil. If plants are grown under unfavorable temperature conditions there is likely to be a delay, or stunting of growth, and an incomplete or ineffective use of the nitrogen. In the case of many plant species stunted plants never recover fully and the final yield is suboptimal.

Deficient moisture may also cause a stunting of early growth, but more often the deficiency occurs during the middle or final quarter of the growth period. This characteristically leads to markedly decreased yields of pasture or hay crops along with decreased quality. In other types of crops the seed or fruit may never form normally or mature satisfactorily. Leaves and stems may develop fairly normally, but at the time that the nutrients are to be transferred into the fruits lack of moisture blocks this process.

The effects of deficient moisture are strikingly shown in dryland areas. Usually moisture is adequate in early spring but inadequate throughout the rest of the growing period, leading not only to low yields but to an ineffective and inadequate use of available nitrogen. Often plants store excess nitrogen as nitrates under such conditions. In fact, even though the level of soil nitrogen is low by normal standards, there may be little or no response to added fertilizers.

Excess soil moisture is often more detrimental than a deficiency, especially in fine-textured soils. By making the soil anaerobic the root tissues are denied their essential supply of oxygen and many plant species will die very quickly, or at least be injured to such an extent that the crop is near a total loss. The sensitivity of plants varies widely; rice, for example, thrives under submerged conditions but corn, tomatoes, and most other field and vegetable crops can tolerate a saturated soil for only a few hours, or at most a few days.

Supply of other nutrients

Since thirteen mineral nutrients that are derived from soil are essential for plant growth, it is obvious that if any one of these, other than nitrogen, is deficient no amount of added nitrogen can take its place. The statement that a chain is no stronger than its weakest link certainly has application here.

Different crops have different requirements for each of the essential elements, and similarly different soils have different capabilities of supplying them. The elements most likely to be deficient are phosphorus and potassium. Next in order are calcium, magnesium and sulfur. The other so-called minor elements are needed in small amounts, and in reasonably fertile soils little attention may need to be given to them. Only actual tests, preferably in the field rather than the laboratory, will show the elements that must be supplied if nitrogen is to be used at maximum efficiency. It is in connection with the supplying of these nutrients that organic matter plays one of its most important roles (Chapter 14). As it undergoes decomposition there is a release of these elements, chiefly phosphorus, sulfur and nitrogen. In addition, the exchange complex, including both the organic and inorganic colloids, holds many of these elements in a highly available condition and ready to be released gradually as the crop needs them. In very sandy soils even some of the minor elements may need to be included regularly in the fertilizer, since these soils are so deficient in organic matter. They are commonly added in slowly available forms to avoid toxicity and also to insure a continuous long-time supply.

Acidity

All nitrogenous fertilizers are effective in neutral or slightly alkaline soils, but at pH values below about 5 the reduced forms of nitrogen are likely to be less effective than nitrates. At even greater acidities none of the fertilizers are very effective. As explained above, this may be attributable to poor ion balance, gaseous loss of nitrogen, or inhibited nitrification. In addition, is the more general fact that most plants simply do not thrive at these high acidities for physiological reasons.

This unfavorable effect of low pH is usually intensified by the nitrogen fertilizers themselves, because most of them increase soil acidity. This may be due to the added acid, as in the case of SO_4^{2-} in ammonium sulfate. It may also be due to the NO_3^- added as neutral salts, or to that formed in the nitrification process. If the NO_3^- formed by nitrification is assimilated by plants and converted into protein, there is no appreciable direct effect on soil pH, but if the acid is leached out in the form of nitrate salts then the increase in soil acidity is marked. Even anhydrous ammonia, which is strongly basic, will produce acidity to the extent that it is nitrified and lost to the drainage waters as calcium nitrate or as some other neutral salt. Even if biologically-fixed nitrogen, present in plants as protein, undergoes decomposition to ammonia and oxidation to nitrate, it increases acidity if leaching occurs. Most of the increase in soil acidity is due to the removal of bases as nitrate salts. The possible reactions are explained in detail by Allison (1931).

Another important cause of increased soil acidity is attributable to the removal of bases from soils in harvested crops. Plants take up nutrients in ionic form and not as neutral salts. The quantity of bases removed is invariably greater than that of acids and therefore the larger the weight of crops removed the greater is the increase in acidity.

Some crops, such as alfalfa and clover, are more base-requiring than are other crops, such as the grasses. Although this removal of bases in harvested crops is a very important source of acidity, the effect is usually not as great as the loss of bases through leaching. At least this is true of cultivated crops, but may not be true of pasture or hay crops where nitrification is usually inhibited, and where leaching is at a minimum.

The continued use of large amounts of nitrogen on cultivated crops often results in the development of very acid subsoils, with accompanying harmful effects on plant growth. As NO_3^-, and to a lesser extent SO_4^{2-}, are leached through the soil they combine with bases wherever they are present, both in the surface and subsurface horizons. The addition of calcium carbonate easily corrects the acidity in the plowed layer, although at some cost, but lime moves downward only slowly, and hence the subsoil tends to remain acid. This is now true of many of the soils of the southeastern states. In such soils root development is curtailed and water-use efficiency is often low. Soils that are kept at a satisfactory pH in the upper root zone, only, may produce fairly good crops, but the yields are usually much less than where the whole soil profile is kept within the optimum pH range.

The slow rate of downward movement of lime is shown by the work of Brown et al. (1956) who applied limestone to the surface of a fine sandy loam grassland. After 9 years the pH had increased to depths of 6, 12, 15 and 24 inches by 2, 4, 8 and 16 tons of limestone per acre, respectively. The movement downward of the lime during the first 2 years was more dependent on lapse of time than on rate of application, although of course the larger applications eventually affected the subsoil to greater depths.

The effectiveness of surface-applied lime in the neutralization of acidity caused by nitrogen fertilizers applied to bermudagrass sod was studied by Adams and Pearson (1969). Lime applied at a rate equivalent to the acidity of the nitrogen source maintained both the pH and exchangeable bases in a loamy sand, but not in a clay loam. Higher rates were more effective in correcting subsoil acidity. The main factors involved were soil type, lime rate, nitrogen source and nitrogen rate. The authors also state that calcium gluconate, sodium nitrate and calcium nitrate, applied on the surface, were effective in the neutralization of subsoil acidity down to a depth of at least 45 cm.

Crop

In making recommendations regarding the use of nitrogen in agriculture, one of the few general statements that can be made is that the nitrogen should be applied at the time that the crop is in most need of it. But, what crop, and for what purpose is this crop being grown? A leafy vegetable crop, for example, that is grown primarily for succulent leaves might respond vigorously to large amounts of nitrogen applied early, whereas if it is grown for seed production a lower level of available nitrogen spread out over the entire growing season might be better. Fortunately, plants have considerable ability to store nitrogen above their immediate needs, and also the ability to move nitrogen from one part to another as the needs change. Nevertheless, the kind, amount, and time of application of nitrogen do vary considerably with the crop grown.

Pasture, fruit, and vegetable or hay crops commonly respond very differently. Applications of 500 or more lb. of nitrogen per acre applied to hay crops may produce excellent yields, but if applied to grain crops might prove toxic, or at least result in lodging. Often excessive leaf and stem production may result in poor fruit yields. This applies to tomatoes and many other crops. The length of the growth period of a crop also often determines the amount of nitrogen required, as well as the best time and method of application.

Some crops, such as tobacco, are especially sensitive to the amount and form of nitrogen applied, and to the relative concentration of the essential nutrients. In this case, crop quality is usually more important than quantity.

Plant population, and genetic characteristics of many crops, such as corn, wheat and sorghums, are also factors that need to be considered in outlining the fertilization program. The new hybrid varieties of the grain crops, and similarly of coastal bermudagrass, will utilize efficiently considerably more nitrogen than the older varieties.

Pests

It scarcely need be mentioned that the presence of insects, diseases, and weeds can severely affect the returns to be expected from applications of nitrogen. Fortunately, insecticides, fungicides and herbicides for the control of most pests are available, but their use on many crops may be at prohibitive costs, and at much less than 100% efficiency of control. Nematode and virus diseases often are so difficult to control that a change in cropping system may be the most practical solution to the problem. A reduction of yield of only 10–15% may often eliminate most of the margin of profit.

Method of application

The methods of application in common use vary widely and include drilling of small amounts of a complete fertilizer with the seed, band applications at the side of the seed, side-dressing, broadcasting, deep applications of anhydrous ammonia or ammonia solutions, plowing under, and foliar applications. The method to be used depends upon the kind of fertilizer, type of crop, time of application (especially before or after seeding), extent of the root system if a crop is present, specific purpose for which the nitrogen is needed (vegetative growth, seed production, or fruit), and various climatic factors.

In choosing the method it is obviously essential that injuries to the plants be avoided, and that the nitrogen be placed near enough to the root system that it can be absorbed fairly rapidly when the crop needs it. Injuries to seedlings, or even to the roots of older plants, following applications of nitrogen may result from excessive concentrations of soluble salts or from increases in soil acidity, as mentioned above. In addition, high concentrations of ammonia, as where anhydrous ammonia is applied, may nearly sterilize the soil in the immediate region. The normal soil flora will reappear within a few days or weeks as the ammonia is adsorbed or utilized by the crop. However, in the intermediate period there may be an accumulation of nitrite–nitrogen, since ammonia is specifically toxic to *Nitrobacter*, the bacterium that oxidizes nitrite to nitrate. Nitrites are very toxic to most plants, especially in acid soils. Nitrites are also subject to losses by volatilization, and to chemical reaction with organic matter to form unavailable compounds.

Surface applications of nitrogen sources, such as urea, that may release ammonia to the air, should also be avoided. Low efficiency from such surface-applied nitrogen may be expected where the nitrogen does not move downward promptly into the soil. This is usually the normal condition in dry land regions, or even in humid regions during periods of subnormal rainfall.

Deep injections of anhydrous ammonia before seeding, or the plowing under of other forms of nitrogen, has yielded excellent results in many instances if the crop to be planted has a rapid-growing and extensive root system (Patrick Jr. et al., 1959). This method is often more economical of labor but, more importantly, it favors a deeper root system, and the more extensive the root system the greater the percentage of the soil moisture that is available to the crop.

Foliar feeding of nitrogen, usually of urea and sometimes of ammonium nitrate, has been practiced to a limited extent in recent years, and with limited success. The rates applied are usually in the order of 10–20 lb. per acre per application, repeated as many times as necessary. Urea is especially readily absorbed but there is little to be gained by this method of application except for special crops or situations. Some truck crops seem to respond quickly to foliar feeding with improved quality of product. This occurs when soils are cold and nitrification is very slow. Most field crops can be fed more satisfactorily through their roots.

Time of application

In the growing of annual crops, such as corn, it has been shown repeatedly that it is well to make certain that there is a supply of nitrogen available immediately after germination. A small amount of a nitrogen-containing fertilizer, often called a "starter" or "pop-up" fertilizer, assures that growth will occur as rapidly as climatic conditions will permit. In the absence of adequate nitrogen, growth is slower and frequently a stunted condition may result, from which the plant may never recover fully even though nitrogen is added later. A starter fertilizer is likely to be quite beneficial even on fertile soils when temperatures are low, nitrification is limited, and the root system is small.

As the plant develops, its nitrogen needs nearly parallel the increase in dry weight, except that young plants usually take up more nitrogen, if available, than is essential for their immediate needs. In older plants the nitrogen percentage decreases. The nitrogen uptake pattern differs with various crops, and this affects the time of application. One application of nitrogen may be adequate for a quick-growing crop, whereas split applications are required for the best growth of long-season crops. Such split applications have been shown to increase the grain:straw ratio in wheat. This result would be expected where soils do not have adequate nitrogen-supplying power late in the summer. Nitrogen is essential for abundant green leaf production during growth and for protein production in the grain.

The fall application of nitrogen fertilizers to Midwestern soils is a practice that has been advocated by the fertilizer industry in recent years. Their main interest is in trying to broaden the period for manufacture, sales, transportation, and application. In doing this, less equipment is required, labor is utilized more efficiently, and the cost of the nitrogen to the farmer is lowered. Fall application also avoids having to carry out this operation during the spring work rush period, and when wet soils may make it impossible to make the application at the most desirable time. Where anhydrous or aqua ammonia are to be injected it is obvious that this can be done more readily in the fall at chosen times, and when there is no possibility of injury to a crop to be seeded the following spring.

The main objection to fall applications of nitrogen is that a considerable portion of it may be lost in the drainage waters or through denitrification. So long as the nitrogen is in the soil as ammonia neither of these possibilities occurs, but oxidation to nitrate occurs fairly rapidly unless the soil is very cold. Nitrate is very subject to loss. On very sandy soils, fall application is usually not recommended except in the drier regions where leaching is negligible, or in the northern states where the soil remains frozen during the winter months. On medium- and fine-textured soils, late fall applications are inadvisable in the southern states because of rapid nitrification, but are usually satisfactory in the northern half of the Corn Belt (Larsen and Kohnke, 1947; Nelson and Uhland, 1955).

The percentage of the fall-applied nitrogen assimilated by the spring crop is seldom as great as when the nitrogen is applied at or near the time of planting, or later as a side-dressing (Pearson et al., 1961). However, if the cost is proportionately less for nitrogen in the fall, the lower recovery can be tolerated. Where nitrogen is applied in the fall in moderate amounts to a cover crop, or where large amounts of wide carbon–nitrogen ratio crop residues are present, the losses may be negligible.

From all that has been said here, the conclusion is obvious that so far as is practical, the best time to apply nitrogen to any crop is when it needs it, bearing in mind that the needs vary with the kind of crop. The quicker the nitrogen is assimilated, the less chance there is of loss as a result of denitrification from wet soils, biological tie-up, or loss in the drainage waters.

Crop residues

The presence of considerable amounts of crop residues having nitrogen contents of less than about 1.5–1.7% (C/N ratio 30 to 25), will reduce the yields of most nonleguminous crops unless fertilizer nitrogen is added to the soil to supply the needs of the microorganisms that decompose them. The amount of nitrogen required for this purpose is a product of the dry weight of the residues multiplied by the difference between 1.7% and the nitrogen content of the residue. For a straw containing 0.5% nitrogen the nitrogen requirement per ton would be about 24 lb. (see Chapter 6).

When should this nitrogen be applied: at the time the residue accumulates or is plowed into the soil, or when the next crop is planted? The answer, with few exceptions, is to fertilize the crop and not the crop residue (Allison, 1955; Sanford et al., 1968). In other words, whatever the amount of nitrogen needed to offset the available nitrogen-depleting effect of the residue, this amount or more should be applied to the crop that follows.

Crop residues that are deficient in nitrogen will decompose in most soils almost as fast without added nitrogen as they would if nitrogen is applied. In doing this they assimilate nitrogen that is constantly being released from soil organic matter. If there is no crop present, they can utilize all or as much as they need of this nitrogen as it is released. This release in a single growing season commonly amounts to 2–3% of the total soil nitrogen, and is ordinarily adequate for the needs of the microorganisms. In periods between crops any such nitrogen utilized in decomposition is prevented from escape in the drainage waters. This is very fortunate. If a crop is present, the microorganisms and crop compete for any soil nitrogen that is made available, and the microorganisms get most of it. This is why it is so essential that nitrogen additions be made with the primary aim of feeding the crop, and not the microorganisms. The latter will look out for themselves.

A few years ago an occasional article was published that expressed the idea that the addition of abundant nitrogen to crop residues would result in holding more of the carbon, and thereby form more humus. This is a fallacy, as pointed out in Chapter 21.

Direct vs indirect application

The highest recovery of added fertilizer nitrogen in the crop is obtained when a readily available form of nitrogen is applied directly to the growing crop, and in such amounts that it will be assimilated promptly.

There are conditions, however, where it is either not convenient to apply the nitrogen at the ideal time or in a manner that is best for the plant, or where other factors take precedence over maximum efficiency of uptake. The use of nitrogen to produce a heavy growth of a green manure crop, especially on soils that are deficient in organic matter, or on soils that are to be used for special crops, such as vegetables, are examples (see Chapter 22).

Comparatively low efficiency of recovery of added nitrogen in the harvested crop, when the nitrogen is first passed through a green crop, is due both to nitrogen losses and to nitrogen tie-up. The losses may be either as gases or as nitrates in the drainage waters. Even if the green crop assimilates the applied fertilizer nitrogen rapidly, this organic nitrogen must undergo mineralization after it is turned under before it can be utilized by the main crop. Opportunities for denitrification and for leaching increase with time.

Nitrogen tie-up is likely to be a more important factor in nitrogen use than is nitrogen loss. Stojanovic and Broadbent (1956), for example, observed that when finely-ground straw was added to soils, 56 lb. of nitrogen per acre per day was immobilized during a 2- to 6-day incubation period. Such immobilization usually decreases as the carbon–nitrogen ratio of the material decreases, but they observed that immobilization was of significant magnitude even with a high nitrogen-containing material such as green corn leaves.

During decomposition most of the nitrogen is immobilized initially, at least, in microbial cells, which in turn are broken down. In the process, a considerable portion of the nitrogen reacts with phenols, quinones, and other ring compounds derived from lignin, or synthesized by microorganisms, to form humic substances, some of which are heterocyclic. Amino acids and ammonia are subject to such chemical reactions, that may be catalyzed by microbial enzymes. In soils with 2:1 clay minerals any ammonia that is formed is also subject to fixation in the clay lattice (see Chapter 8 and 11).

Much of the nitrogen that is immobilized is not available for crop use, as has been repeatedly demonstrated (Fribourg and Bartholomew, 1956; Jansson, 1963; Broadbent, 1966; and Broadbent and Nakashima, 1965, 1967, 1968). Broadbent and Nakashima (1967) found that where straw was added to soils that were incubated in the greenhouse, as much as two-thirds of the fertilizer nitrogen remained in the soil after nearly 1.5 years of continuous cropping.

In other experiments, Broadbent and Nakashima (1967) incubated soils to which straw and tagged potassium nitrate had been added, and at intervals over a period of 592 days leached out the nitrogen. The results for the Aiken clay loam are shown in Fig. 23.2.

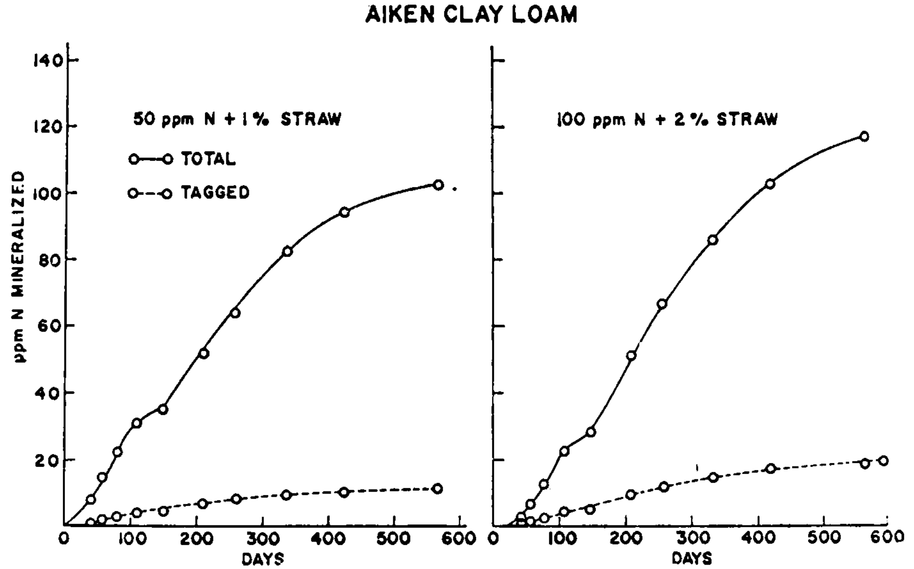

Fig. 23.2. Cumulative nitrogen mineralized in Aiken clay loam fertilized with tagged potassium nitrate. (From Broadbent and Nakashima, 1967.)

Essentially all of the added tagged nitrogen was immobilized within the first 10 days, and hence any mineral nitrogen obtained in subsequent leachings was considered to have resulted from mineralization of organic nitrogen. It will be observed that the quantity of this immobilized tagged nitrogen that was later mineralized represented only a small portion of the total.

In the experiments of Fribourg and Bartholomew the mean efficiency of freshly-cut alfalfa tops as a source of nitrogen for corn was only 34% of that of ammonium nitrate; red clover and soybean straw gave even lower yield increases, and oat hulls decreased corn yields due to nitrogen immobilization. The residual nitrogen recovery of these materials the second year in the order given above were approximately 7.5, 3.5, 2 and 0% of the added nitrogen. All, or nearly all, of the nitrogen that was not recovered during the two growing seasons remained in the soil as a part of soil organic matter.

Only a few years ago soil scientists were very much puzzled to explain the frequent failure of crops to benefit to the extent expected from residual soil nitrogen from a preceding cash crop, or from a green manure crop. Low recoveries of such nitrogen were often observed even where leaching was negligible, and where there was little reason to expect appreciable gaseous losses. Recent tracer studies, earlier mentioned in part, have shown that nitrogen immobilization by the mechanisms mentioned serves as the answer to most questions raised. The nitrogen that reacts with ring compounds, especially that locked in the rings, is evidently not easily released in forms that the plant can use. Continued polymerization of these humic substances further decreases the availability of the nitrogen (see Chapter 8).

It is also well to bear in mind that present evidence shows that the nitrogen content of humic substances is not a constant value; the more amino acids, ammonia and possibly several other nitrogenous substances present in the soil, the higher the nitrogen content of these humic substances. If further research supports this view, then it follows that nitrogen compounds can react with aromatic compounds in the soil without there necessarily being a measurable increase in total humus. This ability of soil organic matter to seize onto nitrogen and other plant nutrients, and to release them slowly later, is one of its most valuable functions or properties. This statement applies particularly to elements other than nitrogen; admittedly this property is often objectionable in the case of nitrogen if immediate results are of primary consideration.

SLOWLY-AVAILABLE FERTILIZERS

Natural organics

The original sources of so-called slowly-available forms of nitrogen consisted chiefly of waste organic materials, such as seed meals, slaughter house products, manures, fish scrap, sewage products and miscellaneous industrial wastes. Some of these, studied by Rubins and Bear, are listed in Table 23.I together with their nitrogen contents, carbon–nitrogen ratios, and water solubility. It will be observed that the nitrogen contents of these materials were in the range of 1.5–14.3% and the carbon–nitrogen ratios were below 33.

The availability of the nitrogen in the various materials, as determined by the nitrification test, is also shown in Table 23.I. In addition, Rubins and Bear made vegetative tests, and these data (not shown here) agreed very closely with the nitrification data. This is the

TABLE 23.I

NITROGEN CONTENT OF VARIOUS ORGANIC MATERIALS AND AVAILABILITY OF THE NITROGEN AS SHOWN BY THE NITRIFICATION TEST (from RUBINS and BEAR, 1942)

Material	*Nitrogen (%)*		*C/N ratio*	*Nitrogen (%) converted to nitrate in*	
	total	*water-soluble*		*20 days*	*40 days*
Seed meals:					
Soybean meal	7.60	84.2	4.7	61	65
Cottonseed meal	7.24	93.0	5.4	49	54
Processed soybean meal	7.69	32.9	7.1	61	66
Castor pomace	5.03	92.8	9.4	60	67
Cocoa meal	2.98	64.1	14.7	14	22
Animal products:					
Hoof meal	14.28	60.7	3.3	65	68
Bone meal	4.16	99.8	3.5	7	10
Dried blood	13.83	97.5	3.5	60	66
Dry fish scrap	9.28	88.6	4.4	59	63
Animal tankage	8.83	64.0	5.3	37	45
Manures:					
Peruvian guano	13.95	43.9	1.3	80	77
Bovung	2.01	69.7	24.4	0	7
Horse manure	1.45	80.0	32.7	–19	–16
Chicken manure	2.25	32.9	36.4	22	30
Sewage products:					
Milorganite	5.66	89.6	6.0	48	53
Sewage sludge	1.78	89.3	13.7	11	16
Miscellaneous:					
Processed tankage	9.76	80.7	5.2	31	35
Garbage tankage	2.66	93.6	13.4	–6	–3
Standard material:					
Urea	–	–	–	87	88

usual observation – if an organic material is not readily nitrified the nitrogen is not likely to be immediately available to a crop.

The data in Table 23.I show that in half of the materials listed, 48–80% of the nitrogen was converted into nitrates within a period of 20 days, and that in the case of a third of the materials the nitrification percent was 60 or above. This compares with 87% for urea. An additional 20 days of incubation raised the average nitrification values by only about 5%, that is to 65% for a material that had shown 60% nitrification after 20 days.

These results show strikingly that most of the higher-grade organic materials used in fertilizers in the past are not actually very slowly available. Most of the nitrogen is rapidly released as ammonia and then oxidized to nitrates almost as rapidly as is urea. The residue is so slowly available that much of it may not be released during the first growing season. The chief factor that determines the availability of the nitrogen in these organic fertilizer materials is the manner in which the nitrogen is combined with, or protected by, other constituents. For plant substances of very low nitrogen content and wide carbon–nitrogen ratio, microbial immobilization is also a major factor in nitrogen availability, provided that the plant materials are readily decomposed.

Natural organics have been prized by gardeners because of the absence of injury due to high salt concentrations. This has usually been much more of a factor in their use than has been the rate of release of their nitrogen. As shown in Table 23.I, the better-grade organics do not release nitrogen as most crops need it, but at rates much in advance of the needs of seedlings that start growth after the addition of the fertilizer. Slow availability of high-grade natural organic fertilizer materials is, therefore, largely a myth; low-grade materials, such as sewage sludge, bone meal and garbage tankage are, however, very slow in releasing their nitrogen.

Artificial nitrogen sources

Much effort has been exerted in recent years by those engaged in nitrogen fertilizer research in an attempt to produce a fertilizer that will release its nitrogen gradually during a growing season. Ideally, such a fertilizer would continually supply the crop with nitrogen at the rate that it could utilize it effectively, and would avoid the necessity for split applications. There is also the hope that such a fertilizer would be less subject to leaching, and possibly to loss in gaseous forms.

It is possible to bring about slow availability by using compounds that are not very water soluble, or decomposed rapidly. By varying the particle size, and thereby the surface area, nitrogen release can be controlled. According to Nelson and Hauck (1965), magnesium ammonium phosphate, crotonylidenediurea, and isobutyridenediurea are compounds of this type that are now produced commercially. Oxamide, which is low in water solubility and contains 32% nitrogen, has also been considered for such use (Engelstad et al., 1964).

The most successful of the artificial slowly-available fertilizers marketed to date are the ureaforms. These compounds resist attack by microorganisms and release their nitrogen over a period of several weeks. They are used now to a considerable extent, and with considerable satisfaction, on golf courses, lawns, gardens and special crops. The cost of the ureaforms, like other slowly-available materials, is considerably higher than other common forms of nitrogen and their general use is prohibited for this reason.

Slow availability can also be brought about by coating available nitrogen compounds with such materials as oils, gums, waxes, paraffins, resins, sulfur, latex, polyethylene, and vinyl acetate (Lunt and Oertli, 1962; Oertli and Lunt, 1962; Nelson, 1965; Nelson and Hauck,1965). These materials may resist microbial attack or they may keep the fertilizer from being dissolved rapidly. In some cases coatings with small pores have been prepared that permit the slow escape of the nitrogen. Such materials lower the nutrient content of the fertilizer, are difficult to manufacture, and are more expensive. Present information indicates that it is very doubtful if the extra benefits to be derived from the use of these materials balance the extra cost of production.

A promising recent development in the manufacture of slow-release fertilizers, according to *Chemical and Engineering News* of January 8, 1968, is the production of a prilled sulfur-coated urea. The claim is made that this can be produced at a price of only 10–20% above that of untreated urea. Only 6–10% sulfur, together with a suitable bonding agent, is needed to coat the urea. If such a material could be produced at this low price it should at least prove of value for turf and certain garden or horticultural crops.

Comparisons of the release of nitrogen from five slow-release nitrogen sources to bluegrass over a 2-year period are reported by Moberg et al. (1970). The recoveries of nitrogen were in the range of 22–54% for these materials in comparison with 27% for activated sewage sludge and 52% for urea. The differences in rates of release of the nitrogen from various sources make it difficult to evaluate their relative merits, particularly when there is no uniform standard; a very slow release might be desirable for some crops but a more rapid one would be preferred for others.

A careful evaluation of present information would seem to indicate that an extensive and general use of manufactured slowly-available fertilizers is probably unlikely (Dahnke et al.,1963). This is true even if the cost differential should be materially reduced. There is no evidence that slowly-available fertilizers are more efficient per unit of nitrogen; in fact, the reverse is usually true. If available nitrogen from inside a coated granule could be released exactly as the plant needed it, there is a possibility of some benefit, but slow availability realized through a slow rate of microbial degradation of a material would certainly decrease efficiency. Every crop varies as to its nitrogen needs throughout the growing season, and even the same crop varies from year to year, or from soil to soil. It would be almost impossible to meet exactly all requirements. Too slow a release would cause partial nitrogen starvation of the crop, and incomplete release during the growing season would lead to fall and winter leaching and tie-up. Incidentally, losses to the drainage waters are usually negligible during the summer months when slowly-available fertilizers are supposed to minimize such losses.

EFFECT OF ADDED FERTILIZER NITROGEN ON UPTAKE OF SOIL NITROGEN BY CROPS

Under greenhouse conditions several investigators (Walker et al.,1956; Jansson, 1958; Walunjkar et al.,1959; Legg and Allison,1959, 1960; Cady and Bartholomew, 1960; Legg, 1962; Stewart et al., 1963) have reported that as mineral nitrogen additions are increased moderately the amount of soil nitrogen in the crop is usually increased, and more of the added nitrogen is immobilized in the soil. This can be demonstrated easily by the use of the ^{15}N-tracer technique. The addition of tagged fertilizer nitrogen increases the ratio of ^{15}N to ^{14}N in the available nitrogen pool, and since soil organisms use the two forms of nitrogen equally well it follows that more ^{15}N is immobilized (see Chapter 6 for discussion of biological immobilization). Higher plants are also feeding on this ^{15}N-^{14}N pool but Legg (1962) has shown that the difference in soil nitrogen uptake by plants is manifested only after the mineral nitrogen pool is almost completely exhausted. The only source of new nitrogen then is that being released from soil organic matter, and the crop utilizes most of it as it is made available. Legg points out that under these conditions competition on the part of the microflora is at a low level, because these organisms get all the nitrogen that they need from root cells and root excretions formed under conditions of abundant nitrogen obtained from the pool that was present earlier. Under field conditions, one would expect that the nitrogen pool would be depleted much less rapidly, because of the larger soil volume and the effect of nitrogen additions, discussed earlier, might be less in evidence or even undetectable.

A rather complete picture of what happens to fertilizer nitrogen added to cropped soil in greenhouse pots is shown in Table 23.II, taken from the data of Legg and Allison (1959, 1960). Immobilization of added tracer nitrogen increased 4–5 times as the nitrogen addition increased 16-fold. Soil nitrogen mineralization (column 9) was essentially a constant as fertilizer nitrogen additions were increased.

In studies by Legg (1962) with 12 soils of different fertility, it was observed that where additions of tagged sodium nitrate were made at rates of 50–200 p.p.m. of nitrogen, the average quantity of ^{15}N left after removal of three crops increased from 14 to 30 p.p.m. The recovery of added nitrogen in the crops plus soil was about 90% in all cases.

METHODS OF DETERMINING NITROGEN RECOVERY

Two methods of determining nitrogen recovery in vegetative tests are commonly used, but they do not determine exactly the same thing. These are the nontracer and tracer techniques. In the nontracer method the nitrogen removed from control soils by the crop is subtracted from that removed from fertilized soils. In the tracer method the recovery of added ^{15}N in the crop plus that immobilized in the soil is determined. The latter method is the better one, and the only one suitable for complete accounting of added nitrogen other than that lost by leaching and as gas. Nevertheless, the simple and comparatively inexpensive nontracer method is the most satisfactory, and the only one that is practical for use by the agronomist who is concerned with fertilizer response, and is not much interested in whether the crop obtains its nitrogen from the fertilizer or from the soil. He wants to know the yield response to fertilizer in a practical way.

The two methods, although not strictly comparable, commonly yield results that agree closely if biological immobilization and chemical fixation (see Chapter 11) are not of major importance. If the tracer method is used the ^{15}N in the soil after crop removal must be determined, or else the results may be low because some of the added nitrogen is tied up in soil organic matter. In Table 23.II (columm 12 vs 14), much lower values were obtained by the ^{15}N procedure than by the nontracer method at all rates of nitrogen addition. This was obviously due chiefly to the use of ammonium-fixing soils, but biological immobilization was also a factor, particularly at the lower rates of nitrogen addition.

TABLE 23.II

THE FATE OF NITROGEN ADDED TO CROPPED SUBSOILS* (from data of LEGG and ALLISON, 1959, 1960)

^{15}N-N added (1)	*N in crops (tops plus roots)*			*N immobilized in soil*			*N in crop or immobilized*			*Recovery of:*			
	^{15}N (mg) (2)	*^{14}N (mg) (3)*	*total (mg) (4)*	*^{15}N (mg) (5)*	*^{14}N (mg) (6)*	*total (mg) (7)*	*^{15}N (mg) (8)*	*^{14}N (mg) (9)*	*total (mg) (10)*	*^{15}N in crop + soil (%) (11)*	*^{15}N in crop (tops + roots) (%) (12)*	*total N in crop above control (tops + roots) (mg) (13)*	*total N in crop above control (tops + roots) (%) (14)*
Myersville soil													
0	–	22.6	22.6	–	–	–	–	–	–	–	–	–	–
37.5	14.1	34.0	48.1	26.1	62.9	89.0	40.2	96.9	137.1	107.2	38	25.5	68
75	35.8	41.6	77.4	35.0	40.7	75.7	70.8	82.3	153.1	94.4	48	54.8	74
150	88.4	53.4	141.8	53.0	32.0	85.0	141.4	85.4	226.8	94.3	59	119.2	80
300	201.2	61.4	262.6	72.9	24.7	97.6	274.1	86.1	360.2	91.4	67	240.0	80
600	460.4	74.5	534.9	102.9	16.6	119.5	563.3	91.1	654.4	93.9	77	512.3	85
Miami soil													
0	–	9.5	9.5	–	–	–	–	–	–	–	–	–	–
37.5	15.0	16.2	31.2	29.1	31.4	60.5	44.1	47.6	91.7	117.8	40	21.7	58
75	38.6	19.4	58.0	38.0	19.1	57.1	76.6	38.5	115.1	102.1	51	48.5	65
150	86.4	24.4	110.8	53.1	15.0	68.1	139.5	39.4	178.9	93.0	58	101.3	68
300	185.7	30.1	215.8	86.2	14.0	100.2	271.9	44.1	316.0	90.6	62	206.3	69
600	390.9	34.8	425.7	160.3	14.3	174.6	551.2	49.1	600.3	91.9	65	416.3	69

*Columns 2,3,4 and 5 are the original analytical data; column 6 is obtained by the relationship: Col.2:Col.3::Col.5: X. Column 9 is the total soil N released and used by the crop or immobilized.

Either low or high nitrogen recovery values may sometimes be obtained by the difference method under certain well-understood conditions but, fortunately, the recovery values are usually not affected markedly. Allison (1966) explains the various possibilities as follows: "At very low levels of soil nitrogen a large percentage of the soil nitrogen that is being continually mineralized is immediately utilized by soil microorganisms in the decomposition of the mass of nitrogen-deficient root hairs and other plant debris that are constantly being formed. The result is that the tops (and roots) have a low nitrogen content, which should lead to high recovery values when these low check values are subtracted from nitrogen-treated values. High values may be obtained, but not always. If the nitrogen addition to the treated plants is low, most of this added nitrogen may be immobilized, and this usually leads to low recovery values even though the control values are low. As the fertilizer nitrogen rate is increased, a larger and larger percentage of this nitrogen is assimilated by the crop rather than by microorganisms, and recovery values by difference are higher. If, in addition, the available nitrogen pool is reduced to near zero, then there is an increased uptake of nitrogen, as already explained, thus making the recovery values as measured by difference still higher. Most of these facts have been observed repeatedly and are well established."

REFERENCES

Adams, F. and Pearson, R.W.,1969. *Soil Sci. Soc. Am., Proc.*, 33: 737–742.

Allison, F.E., 1931. *J. Am. Soc. Agron.*, 23: 878–908.

Allison, F.E., 1955. *Soil Sci. Soc. Am., Proc.*, 19: 210–211.

Allison, F.E., 1957. In: *Soil – Yearbook of Agriculture, 1957.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., pp. 85–94.

Allison, F.E., 1964. *Agric. Sci. Rev.*, 2: 16–23.

Allison, F.E., 1966. *Adv. Agron.*, 18: 219–258.

Bartholomew, W.V. and Clark, F.E., 1965. *Soil Nitrogen. Agronomy*, 10: 615 pp.

Broadbent, F.E., 1966. *Hilgardia*, 37: 165–180.

Broadbent, F.E. and Nakashima, T., 1965. *Soil Sci. Soc. Am., Proc.*, 29: 55–60.

Broadbent, F.E. and Nakashima, T., 1967. *Soil Sci. Soc. Am., Proc.*, 31: 648–652.

Broadbent, F.E. and Nakashima, T., 1968. *Soil Sci. Soc. Am., Proc.*, 32: 388–392.

Brown, B.A., Munsell, R.I., Holt, R.F. and King, A.V., 1956. *Soil Sci. Soc. Am., Proc.*, 20: 518–522.

Cady, F.B. and Bartholomew, W.V., 1960. *Soil Sci. Soc. N.C., Proc.*, 3: 44–51.

Dahnke, W.C., Attoe, O.J., Engelbert, L.E. and Groskopp, M.D., 1963. *Agron. J.*, 55: 242–244.

De Wit, C.T., Dijkshoorn, W. and Noggle, J.C., 1963. *Versl. Landbouwk. Onderz.*, 69: 1–68.

Donald, L., Stangel, H.J. and Pesek, J.T., 1963. In: *Fertilizer Technology and Usage.* Soil Sci. Soc. Am., Madison, Wisc., pp. 75–129.

Engelstad, O.P., Hunt, C.M. and Terman, G.L., 1964. *Agron. J.*, 56: 579–582.

Fribourg, H.A. and Bartholomew, W.V., 1956. *Soil Sci. Soc. Am., Proc.*, 20: 505–508.

Harmsen, G.W. and Van Schreven, D.A., 1955. *Adv. Agron.*, 7: 299–398.

Jansson, S.L., 1958. *Ann. R. Agric. Coll. Swed.*, 24: 101–361.

Jansson, S.L., 1963. *Soil Sci.*, 95: 31–37.

Jansson, S.L., Hallam, M.J. and Bartholomew, W.V., 1955. *Plant Soil*, 6: 382–390.

Larsen, J.E. and Kohnke, H., 1947. *Soil Sci. Soc. Am., Proc.*, 11: 378–383.

Legg, J.O., 1962. Paper presented before: Div. 3, Soil Sci. Soc. Am., Ithaca, N.Y.

Legg, J.O. and Allison, F.E., 1959. *Soil Sci. Soc. Am., Proc.*, 23: 131–134.

Legg, J.O. and Allison, F.E., 1960. *Trans. Int. Congr. Soil Sci., 7th*, 3: 545–550.

Lunt, O.R. and Oertli, J.J., 1962. *Soil Sci. Soc. Am., Proc.*, 26: 584–587.
McFee, W.W. and Stone Jr, E.L., 1968. *Soil Sci. Soc. Am., Proc.*, 32: 879–884.
Moberg, E.L., Waddington, D.V. and Duich, J.M., 1970. *Soil Sci. Soc. Am., Proc.*, 34: 335–339.
Nelson, L.B., 1965. *Adv. Agron.*, 17: 1–84.
Nelson, L.B. and Uhland, R.E., 1955. *Soil Sci. Soc. Am., Proc.*, 19: 492–496.
Nelson, L.B. and Hauck, R.D., 1965. *Agric. Sci. Rev.*, 3: 38–47.
Noggle, J.C., 1966. *Soil Sci. Soc. Am., Proc.*, 30: 763–766.
Oertli, J.J. and Lunt, O.R., 1962. *Soil Sci. Soc. Am., Proc.*, 26: 579–583.
Parr, J.F., 1967. *Soils Fert.*, 30: 207–213.
Patrick Jr., W.H., Sloane, L.W. and Phillips, S.A., 1959. *Soil Sci. Soc. Am., Proc.*, 23: 307–310.
Pearson, R.W., Jordan, H.V., Bennett, O.L., Scarsbrook, C.E., Adams, W.E. and White, A.W., 1961. *U.S. Dep. Agric., Tech. Bull.*, 1254: 1–19.
Rubins, E.J. and Bear, F.E., 1942. *Soil Sci.*, 54: 411–423.
Sanford, J.O., Bruce, R.R. and Myhre, D.L., 1968. *J. Soil Water Conserv.*, 23: 94–96.
Stevenson, F.J., 1957. *Soil Sci.*, 83: 113–122.
Stewart, B.A., Johnson, D.D. and Porter, L.K., 1963. *Soil Sci. Soc. Am., Proc.*, 27: 656–659.
Stojanovic, B.J. and Broadbent, F.E., 1956. *Soil Sci. Soc. Am., Proc.*, 20: 213–218.
Tiedjens, V.A. and Robbins, W.R., 1931. *N. J. Agric. Exper. Stn., Bull.*, 526: 1–46.
Walker, T.W., 1956. *J. Sci. Food Agric.*, 7: 66–72.
Walker, T.W. Orchiston, H.D. and Adams, A.F.R., 1954. *J. Br. Grassland Soc.*, 9: 249–274.
Walker, T.W., Adams, A.F.R. and Orchiston, H.D., 1956. *Soil Sci.*, 81: 339–351.
Walunjkar, W.G., Bartholomew, W.V. and Woltz, W.G., 1959. *J. Indian Soc. Soil Sci.*, 7: 65–72.
Whitehead, D.C., 1970. The role of nitrogen in grassland productivity. *Commonwealth Bur. Pastures Field Crops Bull.*, 48: 202 pp.

Chapter 24

TILLAGE

INTRODUCTION

The practice of tillage dates back to the beginning of history, and was well-established in Mesopotamia at least as early as about 2000 B.C. (see Chapter 1). Frequent reference is made to the practice in both the Old and New Testaments.

The first tillage tools were crude implements of stone, wood, and possibly bones and shells, used by man to eliminate weeds and to chop or dig an inch or so of the soil surface to fit it for seeding. At a later date, animals were used to pull crude crooked-stick plows, which in time were fitted with metal points or edges. The introduction of iron for use in tillage machinery greatly improved the efficiency of tillage instruments, and increased the areas that could be farmed yearly. But cultivation even during medieval times was, by our present standards, a rather crude operation and involved little more than the scratching of the surface. In fact, the operation was avoided to as great an extent as possible by leaving much of the area in pasture or by broadcast seeding of small grains. Some of the farming was done according to a modified system of shifting cultivation, or was even nomadic.

Modern tillage systems had their origin in the 18th century when the moldboard plow was invented. A factory for its production was opened in Scotland in 1760, but it was not until at least 30 years later that many of the plows were in use. This plow is based on such an obvious and simple principle that it seems strange to us that its invention was so long delayed. The first of these plows was a rather crude instrument, but marked improvements were soon offered. The moldboard plow was so effective in burying weeds and trash, and in forming a good seedbed comparatively easily, that it practically revolutionized agriculture. Simultaneously, many other agricultural instruments were invented that aided in seedbed preparation, seeding, and cultivation of row crops. With the gradual substitution of mechanical power for animal power, and the perfection of many kinds of harvesting machinery, modern agriculture rapidly blossomed into its present state of high efficiency.

TILLAGE DEFINED

Anyone who attempts to discuss tillage is considerably handicapped by the lack of an exact, narrow definition of the term, and by a variation in usage of this and related terms in different communities. According to Webster's *Dictionary* to till means "to turn or stir (as by plowing, harrowing, or hoeing) and prepare for seed; to sow, dress, and raise crops from; and to cultivate." By this definition the terms till, plow, cultivate, and even seed are nearly synonyms.

The term tillage, as used here, will therefore include all operations involving manipulation of the soil during seedbed preparation and subsequent growth of crops. These include subsoiling, deep plowing, ordinary moldboard plowing, discing, harrowing, compacting, seeding and the miscellaneous operations involving cultivation and hoeing of the growing crop. Numerous specialized tillage machines, designed for special crops and for special purposes, are in common use but need not be listed here. Since the term plowing is most often used to refer to pre-seeding operations (involving especially the moldboard plow), and the term cultivation to refer to the subsequent stirring of the soil around growing plants, this terminology will be used here to the extent that seems feasible.

PURPOSES OF TILLAGE

A certain amount of tillage is essential at some stage in the growing of almost all crops except, perhaps, in some cases for tree, shrub, vine, and briar crops. The greatest need is usually at the starting stage when the crop must be set out or seeded, and when it has minimum ability to compete with other vegetation. The chief purposes of tillage are discussed by Raney and Zing (1957), and are also considered below. Some of the main factors that need to be considered in a tillage system for a crop such as corn are discussed by Larson (1962).

To prepare a suitable seedbed

The preparation of a seedbed may involve the killing of native vegetation, weeds, a sod crop, or another crop in the rotation. If a newly-cleared area is involved, the work required can be enormous. However, in most cases the moldboard plow, followed by one or more harrowing, compacting or smoothing operations, is all that is needed for the elimination of the remains of previous crop and the formation of a suitable seedbed. In many regions the moldboard plow can be, and is being, eliminated, as mentioned later on p. 496. If row crops are to be grown, it may not be necessary to convert the entire surface soil into perfect condition, but only a narrow band where the seed are to be planted. A good seedbed in this narrow band at the time of seeding is essential, but may be of minor importance later, provided weeds are kept under control.

A seedbed should, ideally, be fine, reasonably compact and free of vegetation and crop residues. Where wind and water erosion are likely to be involved in a major way the residues may need to be kept on the surface, and this usually results in a seedbed that is less than ideal, but yet adequate for seed germination and seedling growth. In regions of limited moisture at seeding time, more attention may need to be given to soil compaction and other ways of assuring that there is adequate moisture for seed germination.

In problem soils the preparation for a crop may involve improvements in the physical condition of the deeper layers of the soil. This commonly occurs in soils that have poor drainage, especially if they have been tilled previously when they were too wet. The installation of tile drains, followed by the seeding of crops that can best tolerate poorly-aerated soils, may be the first requirement. Grass crops are usually best suited to this type of environment. They often improve aggregation to the point where other field crops can be grown satisfactorily. Where a hardpan exists, deep plowing may be of some benefit initially.

Thorough cultivation of crops was for centuries accepted as a very essential step in the production of high yields. This was attributed largely to the improvement of the physical condition of the soil. In recent years this idea has been largely discredited. Improved physical condition of the soil, if it occurs, is now recognized as likely to be one of the lesser benefits.

Cultivation alone probably rarely has a beneficial effect on aggregate formation. Physical forces, probably exerted slowly, are required to form aggregates, but polysaccharides and humic materials are necessary to stabilize any that are formed. As stated previously, it is in grass sods, where soils are left untilled for years, that aggregate formation reaches its highest level. In tropical soils, iron instead of organic matter may act as the binding agent. As tillage tools pass through soils the chances of aggregate destruction are far greater than those of formation (see Chapter 16).

To incorporate manures and fertilizers with soil

When green manures are grown for soil improvement they are usually most effective if incorporated into the soil while still in the succulent stage. The chief exceptions to this practice are where erosion problems make it essential that the crop remain for soil protection, or where it is not feasible to plant a crop promptly to utilize the nutrients released from the decaying green crop. In late fall, for example, it may be better to allow the green manure crop to remain undisturbed until the following spring.

Green manure crops are commonly incorporated into the soil by means of the turn plow or the disc harrow. Either implement is reasonably satisfactory for the job except where the crop is very heavy and woody. In this case the moldboard plow is likely to be more effective, but the choice of implement is dependent to a considerable extent on the cropping system that is to follow. The disc harrow does a better job of mixing the green crop with the soil. The moldboard plow buries the green crop in a largely unmixed layer, and leaves the exposed soil to dry out because of broken capillarity. If the green crop is heavy, the following crop should not be planted for at least two or three weeks, and even then additional operations may be needed to prepare a satisfactory seedbed.

Animal manures are also usually most effective when incorporated into the soil if conservation of the nutrients is the primary aim. Discing into the soil immediately after application is usually the most effective practice. This provides for good contact and mixing at a depth sufficient for capillarity in the soil to maintain good moisture conditions and rapid nitrification. Under many conditions it is often easier to broadcast the manure on the unplowed field and turn it under. This is a fairly satisfactory procedure provided that the manure is exposed to the weather for only a short period, and provided the crop that follows has a sufficiently extensive root system to utilize the nutrients as released.

Animal manures are sometimes used as trash mulches and merely left on the surface. In such cases decomposition is retarded because of lack of moisture, and some of the ammonia formed may be volatilized. Most of the nutrients are, however, leached into the soil and any losses sustained are balanced against the benefits derived from soil protection against erosion. The more bedding material in the manure, the more effective this type of use is likely to be.

Tillage also aids in many operations involving the use of commercial fertilizers. If these materials are applied before plowing, or during plowing by means of fertilizer attachments, the moldboard plow is used. If they are applied at the time of seeding, the seed drill acts in a limited way as a tillage implement. Sidedress, or broadcast, applications of fertilizer to the growing crop may also be followed by a shallow cultivation for the purpose of better mixing with moist soil. If fertilizers containing urea are applied, it is important that they be mixed with the soil to avoid loss of ammonia from the urea.

To eliminate weeds

Aside from seedbed preparation, the control of weeds has long been the most important reason for tillage, particularly of cultivated crops. The comparatively recent perfection of herbicides has provided another and often more satisfactory method of weed control, and thus made cultivation a far less important operation. This statement applies chiefly to field crops where spraying operations can be conducted on an extensive scale, and where the herbicide chosen can be selected on the basis of its effect on a single crop. Where several crops are grown in limited areas, as in a vegetable garden, the control of weeds by means of herbicides may not be feasible unless the operation can be conducted a considerable time prior to seeding, when no crops are present in the immediate vicinity.

Weeds compete with crops for water, nutrients, and light. The competition for water is most harmful in regions or seasons of limited rainfall. If the soil is very dry in the spring the damage may be lessened because of limited germination of the weed seeds. On the other hand, if spring moisture permits good germination and abundant weed growth, and is followed by a dry summer, the damage can be very severe. The drain on the nutrient supply is roughly proportional to the dry weight of the weed growth, and for every pound of dry matter produced by weeds there is a corresponding loss of dry matter in the crop. The competition for light is a lesser factor than for water and nutrients, because severe shading occurs only when the weeds are taller than the crop and dense, and by the time this occurs the crop has already been severely damaged. Crop damage from weeds is likely to be most severe in the early stages of growth, since a stunted plant seldom recovers from the shock.

In the control of weeds the moldboard plow has long been considered as a very effective tool. It not only kills weeds by burying them, but this operation can also be used to prevent germination. The benefits derived from turning under weed seed may be only temporary, since the next plowing returns many of these to the surface; and most weed seeds retain their vitality for several years. The author has frequently observed that most of the weed growth in a given area can be eliminated by merely limiting soil disturbance to the upper inch for three or four years, and preventing new seeds from forming. If such a soil is inverted, the weed growth can be extremely abundant.

DEEP PLOWING AND SUBSOILING

Much research (Chilcott and Cole, 1918; Hume, 1943; Kohnke and Bertrand, 1956; Russell, 1956; Wells, 1956; Younts and York Jr., 1956; Brind, 1957; Robertson et al., 1957; Fehrenbacher et al., 1958; Patrick Jr. et al., 1959; Jamison et al., 1960; Larson et al., 1960; Hobbs et al., 1961; and Brill et al., 1965), has been conducted on the effects of deep plowing and subsoiling on crop yields. These studies, which were often initiated in the hope of securing marked benefits, have almost always yielded disappointing results.

The numerous reasons advanced originally for expecting marked benefits were many. They included: (1) the provision of a medium in which plant roots could ramify more readily; (2) improved aeration; (3) improved infiltration of water; (4) better drainage; (5) breaking up of hardpan and impervious plowsole; (6) bringing to the surface clay material to serve both as a new source of mineral nutrients and to provide more colloidal material for sandy soils; (7) increasing the depth of topsoil through incorporation of organic materials and fertilizers at lower depths; and (8) introduction of lime to very acid subsoils.

The experimental results show that deep plowing of most reasonably normal soils does not have much effect on the depth to which roots penetrate. The depth of penetration does vary markedly with both soils and crops, but depth of plowing has a minor effect except where there is a very impervious layer. This fact is one of the main ones advanced by the advocates of no plowing or minimum tillage.

Better aeration in the soil is usually provided through deep plowing, but there is little evidence that unplowed, well-drained, soils do not already have adequate aeration for most crops, except in very heavy soils during very rainy periods (Grable, 1966). If roots are able to move readily through the soil between aggregates, air can also diffuse rather readily through these same spaces. Recent studies indicate that the inside of aggregates may be somewhat oxygen-deficient at times, but the roots do not grow inside these to any extent, if at all, and furthermore, there is no certainty that tillage will appreciably change this situation.

Aeration involves the removal of carbon dioxide, as well as the providing of oxygen, and carbon dioxide has been reported to be toxic to certain plants at levels possibly as low as 1–5%. Since this gas is much more soluble in water than is oxygen, it is possible for its concentration in the soil solution to be comparatively high. Bergman (1959), however, discusses this subject and concludes that where experiments have provided for adequate oxygen, they have shown that "carbon dioxide, except at concentrations rarely found in soils, very generally has no important effect on growth of roots, absorption of mineral nutrients, or other physiological processes." Grable (1966) also cites several references in support of the view that carbon dioxide rarely accumulates to toxic levels in soils. He states that many data suggest that carbon dioxide stimulation of plant growth is more common than carbon dioxide toxicity.

Bergman (1959) emphasizes the need for further research on the relation of oxygen and carbon dioxide content of soils to the infection of roots by disease-producing organisms, since many factors, not fully understood, are involved. Grable (1966) also stresses the importance of the interrelations between soil aeration and the infection of crops by pathogens, and suggests that "soil water content per se may be more critical than soil aeration." He calls attention to the great variation in physiological response of plants to different levels of carbon dioxide and oxygen. Furthermore, gaseous transfer through air spaces within plants may in some cases make them independent of soil aeration.

Infiltration of water into medium- or fine-textured soils may be increased for a time at least by ordinary plowing and cultivation, but this effect is usually temporary unless the surface is protected by a vegetative cover or mulch. However, the bringing to the surface of much clay by deep plowing may result in the formation of a hard crust, that will make water entrance more difficult than otherwise. The less organic matter on the surface the slower the rate of water penetration. Chilcott and Cole (1918) reported that under dry land conditions deep tillage not only had no value in overcoming drought, but tended to reduce the yields in those seasons of below average production.

Better drainage is one benefit that may be realized from deep plowing and subsoiling under conditions where this operation breaks up an impervious layer. No appreciable improvement would be expected in more nearly normal soils. Unless a hardpan exists, the roots of crops, such as sweet clover and alfalfa, may be able to penetrate to such an extent that drainage is improved. Where subsoiling is practiced, the operation does not ordinarily result in permanent improvement, since the subsoil materials tend to become cemented together within a year or so.

Emphasis is sometimes placed on the desirability of gradually deepening a soil in order to bring a fresh supply of minerals to the surface. There is little evidence that this is of much practical importance, although undoubtedly availability is increased by surface exposure. In terms of saving on the purchase of fertilizers, the operation would certainly repay only a very small percentage of the cost of deep plowing.

In very sandy soils that are underlain by clay, deep plowing is sometimes practiced for the purpose of incorporating some of the clay with the sand. This sometimes results in increased yields for a time, but is not likely to have much effect in controlling erosion (Chepil et al., 1962).

Woodruff and Smith (1947) concluded from their studies of a claypan soil that lack of lime in the subsoil was of greater significance than was the poor physical condition. They suggested that subsoil shattering, together with deep placement of lime and fertilizer, would probably allow corn to be grown satisfactorily.

Kohnke and Bertrand (1956) observed a marked increase in root growth from subsoiling when fertilizers were applied, but there was only a slight effect without fertilizers. These treatments also increased porosity for over two years, and more moisture was present, indicating less runoff. Subsoil fertilization resulted in increased yields in many cases, but the increases were not consistent.

Younts and York Jr. (1956), similarly, failed to demonstrate any pronounced effect of deep placement of lime and fertilizer upon plant growth or upon root activity. Corn yields were unaffected by the deep placement but crimson clover yields were increased somewhat.

Soils that have received heavy applications of fertilizers over the years, as in many sections in the southeast states, often have subsoils that are so acid, or even toxic due to high aluminum and manganese, that root penetration is limited (Foy and Brown, 1963, 1964). Deep plowing or subsoiling with accompanying additions of lime is one method by which the bad conditions can be improved. Applications of lime to the upper 4- to 6-inch layer of soil will commonly have little first-season effect on the subsoil, and if roots do not grow there extensively water-use efficiency and crop yields will be low.

Deep plowing (8–12 inches with a moldboard plow), if properly done over a period of a few years, will gradually increase the depth of the topsoil. For most field crops, as stated above, this may have little effect but for certain special crops, such as vegetables, there is some evidence that this is beneficial on some soils. Crops, such as carrots, parsnips, and sweet potatoes, that prefer a loose soil, may grow better in a deep topsoil, well-supplied with humus, than in a shallow one. The importance of such deep soils in gardening is still uncertain because most deep plowing experiments have been conducted with field crops, and often in soils where root penetration was not an important factor. Needless to say, there is a marked difference in the response of different kinds of plants to the soil environment.

The economics of deep plowing and subsoiling is also very unfavorable. These operations cost more than ordinary shallow plowing, may be in addition to it, and the effects are usually of comparatively short duration (Jamison et al., 1960). As Chilcott and Cole (1918) emphasize, the expense is not justified under ordinary field conditions.

TIME OF TILLAGE

The physical condition existing in a loam or clay soil is very dependent on whether past tillage operations were conducted at the proper time – that is, when neither too wet nor too dry. Very sandy soils can be plowed at almost any time but this is not true of the heavier soils; they are either too wet or too dry most of the time. If these heavy soils are too dry, tillage is not very effective in making a fine seedbed free of clods. If the soil is too wet, portions of it are puddled, leaving clods when dry. A shiny, slick surface left by the moldboard plow serves as visible evidence that the soil was plowed when too wet.

The presence of abundant humus in a soil loosens the soil and lengthens the time when clay soils can be plowed satisfactorily. This is especially in evidence in garden soils where large amounts of manures have been applied over the years. Although a single application of organic matter, whether as animal manure or green manure, may have little detectable effect, there is a marked accumulative effect.

The plowing of large acreages of land often presents problems because the soil in all sections of the field is not at the same moisture content. The higher areas may be at optimum moisture content, whereas the lower areas are much too wet. Or, more likely, there are low-lying depressions where drainage is poor and where the soil is too wet most of the time. The farmer often plows through these wet spots for the obvious reason that it may not be practical to try to by-pass them. Even tile drainage of these wet areas is not always completely satisfactory.

Very wet, rainy, spring seasons present a major problem and often delay plowing and planting to such an extent that the crop has inadequate time for maturing. This has led to a considerable increase in fall plowing when there is more opportunity to select a time when the soil is at the optimum moisture content. This speeds up early spring planting but, unfortunately, it also leaves the soil unprotected during the winter months. The advantages must be weighed against the disadvantages with relation to each individual soil and crop.

AMOUNT AND DEPTH OF CULTIVATION OF CROPS

Frequent and thorough cultivation was until comparatively recently considered as the mark or criterion of good farming. Because the more prosperous farmers put much emphasis on cultivation, it was generally assumed that this operation was of major importance. We now know that this is not the case. If weeds are controlled by means of herbicides or otherwise, cultivation can usually be dispensed with, or at least be reduced to a minimum, without serious effect on yields (Blake and Aldrich, 1955). As pointed out above, stirring the soil does release available nutrients through accelerated destruction of soil organic matter, but this acceleration can seldom be classed as a benefit. Nutrients can better be supplied through the growth of legumes and the use of commercial fertilizers.

In the early years of the present century much emphasis was placed on the maintenance of a dust mulch by frequent hoeing or cultivation. Aside from the killing of weeds, such a dust mulch was considered as a water conservation measure. It was reasoned that moisture continually rises by capillarity from the subsoil or water table to the surface, and much of it is lost to the air by evaporation from an undisturbed soil surface. By frequent shallow cultivation it was hypothesized that the dry, loose surface soil would break the capillarity and thus hold the moisture in the root zone.

A few experiments by soil physicists soon showed that there is no sound basis for the dust mulch theory. Water will not rise by capillarity more than about 18–24 inches in very fine-textured soils, and considerably less than this in silt and sandy soils. Water tables are usually much deeper than this. Furthermore, water movement through a soil that is at or below field capacity is exceedingly slow. The demonstration that capillarity is of far less importance in soil than previously supposed automatically de-emphasized the importance of the dust mulch. We now know that soils dry out from the surface downward and the amount of water so lost is almost independent of the nature of the surface, provided that it is either a dust mulch or a hard dry crust. An apparent exception to this statement is in soils that form cracks, but this is really not an exception; the cracks merely increase the evaporation surface. If shallow cultivation eliminates the cracks, some slight benefits attributable to moisture conservation would be expected.

A discussion of the factors influencing the evaporation of soil moisture is presented by Hide (1954). He states that the rate of evaporation of moisture from soil is influenced by: (1) the difference in vapor pressure between the layer from which water is evaporating and that of the turbulent atmosphere; and (2) the resistance to vapor flow of the intervening layer. The vapor pressure difference is associated with temperature of the layer from which evaporation is taking place and the temperature and relative humidity of the turbulent air. While the surface is kept moist, the principal resistance to vapor flow is caused by the thin layer of nonturbulent air adjacent to the surface. Resistance increases rapidly as the surface dries, and the water vapor must move through a layer of dry soil.

It scarcely need be pointed out that the loss of water from a damp soil surface is dependent upon the amount of heat that reaches it, and on the evaporating power of the air. The loss continues at a near-constant rate only so long as the soil conducts water to the surface fast enough to keep it thoroughly moistened. If the rate of movement of the water upward lags behind the rate of evaporation, the soil surface soon becomes dry. When this occurs the water vapor is produced under the soil surface instead of at the surface, and can diffuse through the dry soil only slowly. The rate of loss of water is affected only slightly by the thickness of the dry layer. Showers that moisten the surface and re-establish capillarity greatly increase evaporation losses until such time as a dry layer again forms.

Cultivation has some effect on soil aeration but less than might be expected. Domby and Kohnke (1956), for example, showed that surface crusts on a silt loam restricted gaseous diffusion only at low moisture tensions. The wetter the soil, the greater was the influence of crusts on diffusion. They state that "except during a period of complete sealing, however, crusted soils actually may permit more rapid diffusion and be better aerated than mulched or other uncrusted soils, because of differences in moisture content."

Regardless of what has been said above, cultivation will always be practiced to a considerable extent for weed control. Such cultivations should be as shallow as possible to avoid cutting off the plant roots that are often largely concentrated in the upper one to three inches of soil. Such root pruning can often more than offset any benefits to be expected from the cultivation.

All of these facts regarding cultivation and movement of moisture emphasize that if soil moisture is to be used efficiently, the roots must go after it; water has little tendency to move to the roots.

SOME EFFECTS OF TILLAGE

Soil compaction and aggregate disruption

The movement of heavy farm machinery over a clay or loam soil can produce a marked deterioration of soil structure and aggregation (Parker and Jenny, 1945). In addition, the plow or cultivator disrupts aggregates. Under optimum moisture conditions, the harm done may not be serious. Also, compaction and aggregate disruption may not be markedly harmful on soils that are too dry, but can be extremely damaging on wet soils. The harm done is usually directly correlated with the fineness or texture, and indirectly with the amount of organic matter in the soil.

Livestock trampling can also cause compaction similar to that resulting from heavy machinery. This type of compacted layer is distinctly different from pan horizons that are developed genetically (Raney et al., 1955); the latter constitute a more serious problem.

The harmful effects of heavy farm machinery and of cultivation under unfavorable moisture conditions tend to accumulate from year to year if cultivated crops are grown continuously (Neal, 1953). Aggregate destruction can occur quickly, whereas aggregate formation is usually a slow process with many factors involved. Freezing and thawing may help to loosen a compact, partly-puddled, soil but these forces alone are seldom adequate; a grass crop in the rotation is commonly the most practical method of restoring good aggregation.

Infiltration

Tillage, either before or after a crop is on the land, loosens the soil, may occasionally improve infiltration for a short time, and sometimes benefits drainage, but the compaction from farm machinery on heavy soils tends to have a reverse effect.

The overall effects of tillage on infiltration are not, however, dependent so much on looseness of the soil as on the nature of the surface (Duley, 1939; Parr and Bertrand, 1960). Immediately after the stirring of the soil the uptake of water may be rapid but the impact of water drops soon results in aggregate destruction, and the surface is largely sealed by the released individual clay particles (Burwell et al., 1968). Water can penetrate such a soil layer only very slowly, whether it remains wet or dries to form a hard crust. During a heavy rain it is not uncommon to see water either standing on, or running off in gullies, from a clay soil that has recently been plowed and seeded, or prepared for seeding. This can occur even though the seedbed is comparatively loose and in good physical condition.

In studies of crusts formed under simulated rainfall, Tackett and Pearson (1965) observed a dense surface layer 1–3 mm thick with a surface thin-skin coat of well-oriented clay. Water permeability of the 0–5 mm layer was about one-fifth that of the soil underneath. In contrast, there was no difference in permeability of the surface and underlying soil compacted by pressure. This emphasizes the aggregate-destroying force of the falling raindrop.

Another benefit sometimes attributed to the dust mulch was that cultivation destroys the surface crust and thereby allows the air to move into the soil more readily. Grable (1966) points out that "most evidence indicates that crusts have little influence on soil aeration." The nature of the surface layer seems to be rather unimportant, unless it is thick relative to total soil depth. He emphasizes that there is usually adequate oxygen under crusts for seed germination, but seedlings may not be able to emerge until the crusts are broken by tillage or softened by water.

A layer of organic matter on the surface, or a growing crop, that absorbs the impact of raindrops, prevents the sealing of the surface. In such a protected soil, infiltration is increased and more of the rainfall is conserved. The capacity for the retention of water against gravity is, however, chiefly a function of particle size and degree of aggregation.

Experiments reported by Parker and Jenny (1945) showed that the incorporation of organic matter as a cover crop or manure in orchards greatly increased the rate of water infiltration, and the improvement was related to the quantity of organic matter applied. Cultivation practices and traffic in the orchard increased compaction and reduced infiltration.

Tillage systems that leave a rough surface in the form of depressions, pockets or furrows that provide numerous obstacles to the flow of water are effective in increasing water uptake by the soil (Burwell et al., 1966). Tillage across the slope accomplishes this to a considerable extent even if no crop residues are left exposed.

Erosion

A freshly-plowed or cultivated field is susceptible to maximum water erosion and gully formation. The clay particles and free organic matter are the first constituents to move to lower levels, but after a very hard rain the entire soil mass in the bottom of the valleys may be transported, leaving only unplowed subsoil in the bottom of the gullies. A dense crop that covers the ground or a layer of organic matter is required to guard against major losses of soil. Erosion is an especially serious problem in unprotected hilly clay soils in warm humid climates.

Wind erosion is also favored by cultivation, particularly in semiarid regions where the soil surface often remains dry and largely exposed for most of the growing season. Well-decomposed organic matter at the surface is readily removed, and this also favors the formation of aggregates that are so small that they are also subject to removal by wind. Much better protection against the wind is realized from the maintenance of vegetative materials on the surface than from mixing them into the soil to increase soil aggregation during the initial stage of their decomposition (Chepil, 1954, 1955; Chepil and Woodruff, 1963). Land that is broken out of a virgin sod is likely to be more erodible than soil that has been under cultivation and subject to wind erosion for many years (Chepil et al., 1952). This is due to the lower organic matter content and to difference in texture and structure of the latter soil following the removal of much of the original A-horizon (see Chapter 27 for a further discussion of erosion).

Soil organic matter oxidation

Cultivation has long been recognized as an effective way of increasing crop yields, especially when commercial fertilizers were not added, but the exact reasons for the increases were not well understood. The best farmers cultivated their soils frequently even when there were few weeds present. Prior to about 40–50 years ago the benefits of tillage were ascribed in large part to the dust mulch produced, but we now know that, aside from weed control, the main reasons that cultivation increased yields was because it released nutrients from the soil, and mostly from the organic portion (see Chapter 8 and 14).

Cultivation increases biological activities in the soil, and this is frequently attributed to better aeration. This is in part true. But cultivation also exposes an inch or so of topsoil to rapid drying, and after each drying there occurs a burst of biological activity for a two- or three-day period following remoistening (Stevenson, 1956; Soulides and Allison, 1961; Birch, 1958, 1959, 1960, 1964; Van Schreven, 1967). This shows that the drying process releases organic compounds, since the amount of biological activity is directly proportional to the available energy supply (Rovira and Greacen, 1957). The exact mechanisms by which the organic matter is released are not known in detail, but apparently much of it comes from the breakdown of soil aggregates that are bound together by humic materials. Soils with clays having 2:1 lattices also have organic matter between the layers, and probably some of this is released. Whether humic materials that exist free of clay particles are affected by drying is not known with certainty, but any such effect is probably minor.

The effect of cultivation, then, is to release considerable nitrogen as ammonia that is subsequently oxidized in large part to nitrates. This release of nitrogen, in addition to the enhanced water supply, largely explains why crops show a sudden spurt of growth when a rain follows a long period of drought, and this occurs even in the absence of cultivation. This release and oxidation of organic matter is in most respects an undesirable result of tillage operations.

Nutrients other than nitrogen are also made available to a significant extent as a result of drying and the increased biological activities. This is true especially of phosphorus, since much of it is present in soil in organic form. Other mineral elements are also released through drying, and as a result of numerous other interactions in the soil.

The supply of available nutrients in soil is also maintained at a considerably higher level than would otherwise be the case as a result of weed elimination. Although cultivation is the means of preventing weed growth, the benefit derived may be due only in small part to the stirring of the soil; the use of herbicides alone may produce almost as great an effect.

Cultivation year after year can markedly lower the soil organic matter content, and as this occurs the soil physical properties can markedly deteriorate. The soil then gradually becomes a continually poorer medium for plant growth. This has usually been the picture in the past but in recent years farming systems, such as continuous corn culture, have been developed that maintain the soil organic matter and fertility. These modern systems are characteristically based on the use of abundant commercial fertilizer together with the return of the large amounts of crop residues that are produced under such an intensive system of farming. In addition, cultivation is usually reduced to a minimum, thereby retarding the destruction of soil organic matter.

Reduction in insect and disease damage

Tillage that is done at the right time and with the proper machinery can sometimes, but not always, help to decrease the injuries resulting from certain insects and diseases (Cole and Mathews, 1938). Chemical treatments are so much more effective, however, that little emphasis is now placed on tillage as a means of pest control.

Late fall plowing, and deep plowing, are damaging to many insects that hibernate in crop residues. Shallow cultivation may also expose insect eggs to drying and thereby destroy many of them. Much can often be accomplished by adjusting tillage operations and seeding time to the life cycle of the insect, so as to affect it at its most vulnerable point.

Operations that bury crop residues may decrease injuries caused by some plant diseases, but this method is rarely very effective. Sewell (1965) gives a good discussion of the effect of altered physical condition of soil on biological control. Cultivation that directly or indirectly increases available nutrients, or the direct application of fertilizers, may have more effect by increasing plant vigor.

MINIMUM TILLAGE

During the past 30–40 years much of the agriculture in the United States that involves the growing of field crops has been changing from a system of comparatively intensive tillage to one of less tillage (Melsted, 1954). The reasons for this are largely obvious from the discussion given in the preceding pages. Basically, the change is the logical follow-up of much research, showing that tillage is far less essential than was previously supposed, and can, in fact, be very harmful under many conditions. This trend toward minimum tillage systems was undoubtedly hastened by the sensational, but largely unscientific and unsupported, statements of Faulkner (1943). His book at least stimulated much research, which has resulted in many changes in our cultural practices.

The term minimum tillage has been defined as the fewest number of operations necessary to produce satisfactory yields. This system of growing crops does not refer to any very specific method of farming, but includes any or all practices that eliminate most of the disturbance of the soil and results in little or no reduction in yields.

Minimum tillage systems are of two general types; those used in dry land farming and those suitable for the humid regions. In the dry land regions the system is commonly designated as stubble- or trash-mulch farming (see Chapter 25). In this case weeds are commonly controlled through shallow cultivation with sweeps and other special equipment. Herbicides may or may not be used.

In humid regions several kinds of special equipment are being used to speed up farming operations, but it is not obligatory that these be used. If only standard plows, cultivators and disc harrows are available, crops can be grown, although less satisfactorily, by minimum tillage methods, provided herbicides are used for weed control. In fact, it was primarily as a result of the perfection of herbicides that most minimum tillage systems as we now know them became possible in humid regions. The equipment used in dry land farming to kill seeds is not satisfactory for use in regions of high rainfall.

An evaluation of minimum tillage ("plow-plant") methods of corn planting using herbicides, made by Fanning and Brady (1963) under humid conditions, emphasized the importance of soil and climatic conditions. They state that "under conditions of good soil drainage, and of drier-than-normal early season moisture, the conventional method gave yields equal to or better than those from plow-planting. The conventional method also gave a much higher stand count and a higher yield on one portion of an experimental field that was exceptionally cloddy after plowing. Where the soil was somewhat poorly drained and/or the season wetter and cooler than normal, the plow-plant method gave superior yields to those obtained from the conventional method of tillage."

With some of the machines developed specifically for use in minimum tillage systems, such as the varitiller, it is possible to apply fertilizer, herbicides and insecticides, as well as plant the seed, in one operation without previous conventional seedbed preparation. Such a machine is suitable for the planting of such crops as corn and beans. Actually, if the herbicide were completely effective, the crop might be grown to maturity without further tillage. In any case, such a machine should at least greatly reduce tillage operations both before and after planting.

The chief advantages usually realized from minimum tillage are that it: (1) reduces compaction; (2) lessens damage to soil aggregation and structure as cultivation is reduced; (3) makes disposal of crop residues less of a problem; (4) eliminates plowsole hardpan formation; (5) increases infiltration if soil surface is left rough or covered with crop residues; (6) decreases the loss of soil organic matter through oxidation; (7) reduces erosion; and (8) lowers the cost of production of crops. In addition, since seeding can be done much more rapidly, unfavorable weather conditions are likely to be less of a handicap at the time of spring seeding.

Some of these benefits are well illustrated by the simulated rainfall experiments of Mannering et al. (1966) who reported that infiltration into a silt loam averaged 24% more, and soil loss 34% less, from minimum tillage than from conventional treatments. After 5 years, soil aggregation, organic matter content, and porosity were slightly higher on minimum tillage plots than on conventional plots. Harrold et al. (1967), similarly, found that no-tillage in comparison with normal tillage of corn conserved water and markedly reduced erosion without adversely affecting corn yields.

The scientific basis for most of these benefits resulting from reduced tillage that are not obvious have been discussed in this chapter. The phases of the subject that relate more specifically to stubble-mulch farming are considered in the chapter that follows.

REFERENCES

Bergman, H.F., 1959. *Bot. Rev.*, 25: 417–485.
Birch, H.F., 1958. *Plant Soil*, 10: 9–31.
Birch, H.F., 1959. *Plant Soil*, 11: 262–286.
Birch, H.F., 1960. *Plant Soil*, 12: 81–96.
Birch, H.F., 1964. *Plant Soil*, 20: 43–49.
Blake, G.R. and Aldrich, R.J., 1955. *Soil Sci. Soc. Am., Proc.*, 19: 400–403.
Brill, G.D., Alderfer, R.B. and Hanna, W.J., 1965. *Agron. J.*, 57: 201–204.
Brind, W.D., 1957. *Soils Fert.*, 20: 241–245.
Burwell, R.E., Almaras, R.R. and Sloneker, L.L., 1966. *J. Soil Water Conserv.*, 21: 61–63.
Burwell, R.E., Sloneker, L.L. and Nelson, W.W., 1968. *J. Soil Water Conserv.*, 23: 185–187.
Chepil, W.S., 1954. *Soil Sci.*, 77: 473–480.
Chepil, W.S., 1955. *Soil Sci.*, 80: 413–421.
Chepil, W.S., Englehorn, C.L. and Zing, A.W., 1952. *Soil Sci. Soc. Am., Proc.*, 16: 19–21.
Chepil, W.S., Moldenhauer, W.C., Hobbs, J.A. and Taylor, H.M., 1962. *U.S. Dep. Agric. Prod. Res. Rep.*, 64: 1–14.
Chepil, W.S. and Woodruff, N.P., 1963. *Adv. Agron.*, 15: 211–302.
Chilcott, E.C. and Cole, J.S., 1918. *J. Agric. Res.*, 14: 481–521.
Cole, J.S. and Mathews, O.R., 1938. In: *Soils and Men – Yearbook of Agriculture, 1938.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., pp. 321–328.
Domby, C.W. and Kohnke, H., 1956. *Soil Sci. Soc. Am., Proc.*, 20: 1–5.
Duley, F.L., 1939. *Soil Sci. Soc. Am., Proc.*, 4: 60–64.
Fanning, D.S. and Brady, N.C., 1963. *Agron. J.*, 55: 348–351.
Faulkner, E.H., 1943. *Plowmans Folly.* Grosset and Dunlap, New York, N.Y., 155 pp.
Fehrenbacker, J.B., Vavra, J.P. and Lang, A.L., 1958. *Soil Sci. Soc. Am., Proc.*, 22: 553–557.
Foy, C.D. and Brown, J.C., 1963. *Soil Sci. Soc. Am., Proc.*, 27: 403–407.
Foy, C.D. and Brown, J.C., 1964. *Soil Sci. Soc. Am., Proc., 28: 27–32.*
Grable, A.R., 1966. *Agron. J.*, 18: 57–106.
Harrold, L.L., Triplett Jr., G.B. and Youker, R.E., 1967. *J. Soil Water Conserv.*, 22: 98–100.
Hide, J.C., 1954. *Soil Sci. Soc. Am., Proc.*, 18: 234–238.
Hobbs, J.A., Herring, R.B., Peaslee, D.E., Harris, W.W. and Fairbanks, G.E., 1961. *Agron. J.*, 53: 313–316.
Hume, A.N., 1943. *S. D. Agric. Exper. Stn. Bull.*, 369: 1–12.
Jamison, V.C., Larson, W.E. and Lovely, W.G., 1960. *J. Soil Water Conserv.*, 15: 247–251.
Kohnke, H. and Bertrand, A.R., 1956. *Soil Sci. Soc. Am., Proc.*, 20: 581–586.
Larson, W.E., 1962. *J. Soil Water Conserv.*, 17: 3–7.
Larson, W.E., Lovely, W.G., Pesek, J.T. and Burwell, R.E., 1960. *Agron. J.*, 52: 185–189.
Mannering, J.V., Meyer, L.D. and Johnson, C.B., 1966. *Soil Sci. Soc. Am., Proc.*, 30: 101–105.
Melsted, S.W., 1954. *Adv. Agron.*, 6: 121–142.
Neal, O.R., 1953. *Adv. Agron.*, 5: 383–406.
Parker, E.R. and Jenny, H., 1945. *Soil Sci.*, 60: 353–376.
Parr, J.F. and Bertrand, A.R., 1960. *Adv. Agron.*, 12: 311–363.
Patrick Jr., W.H., Sloane, L.W. and Phillips, S.A., 1959. *Soil Sci. Soc. Am., Proc.*, 23: 307–310.
Raney, W.A. and Zing, A.W., 1957. In: *Soil – Yearbook of Agriculture, 1957.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., pp. 277–281.
Raney, W.A., Edminster, T.W. and Allaway, W.H., 1955. *Soil Sci. Soc. Am., Proc.*, 19: 423–428.

Robertson, W.K., Fiskell, J.G.A., Hutton, C.E., Thompson, L.G., Lipscomb, R.W. and Lundy, H.W., 1957. *Soil Sci. Soc. Am., Proc.,* 21: 340–346.
Rovira, A.D. and Greacen, E.L., 1957. *Aust. J. Agric. Res.,* 8: 659–673.
Russell, E.W., 1956. *J. Agric. Sci.,* 48: 129–144.
Sewell, G.W.F., 1965. In: K.F. Baker and W.C. Snyder (Editors), *Ecology of Soil-borne Plant Pathogens.* Univ. Calif. Press, Berkeley, Calif., pp. 479–494.
Soulides, D.A. and Allison, F.E., 1961. *Soil Sci.,* 91: 291–298.
Stevenson, I.L., 1956. *Plant Soil,* 8: 170–182.
Tackett, J.L. and Pearson, R.W., 1965. *Soil Sci.,* 99: 407–413.
Van Schreven, D.A., 1967. *Plant Soil,* 26: 14–32.
Wells, C.B., 1956. *J. Aust. Inst. Agric. Sci.,* 22: 247–251.
Woodruff, C.M. and Smith, D.D., 1947. *Soil Sci. Soc. Am., Proc.,* 11: 539–542.
Younts, S.E. and York Jr., E.T., 1956. *Soil Sci.,* 82: 147–155.

Chapter 25

USE OF MULCHES

INTRODUCTION

The term mulch, as used here, refers to any naturally-formed, undisturbed soil covering; any material added to serve as a soil cover; and to crop residues left in part on the surface as dead or dying materials. This definition is, therefore, broad enough to include essentially all organic and inorganic materials that serve as soil covers. The main emphasis here, however, is on conventional mulches of organic materials, where the soil is usually completely covered to various depths by plant materials added from outside sources. Reference will also be made to stubble- or trash-mulches, where the soil surface is usually only partially covered. Whether the soil is completely or only partly covered, most of the effects produced are very similar, but differ in degree.

Much research in recent years has shown that under many conditions a very effective method of utilizing crop residues is as mulches for growing crops, although the economic factors are often not favorable. The mulch system provides for the many benefits to the crop and soil of keeping the soil surface protected for as much of the time as possible. As the crop residues are decomposed they pass gradually through the stage of active organic matter, and then to more resistant humus. If the mulched soil is left undisturbed, much of the organic matter tends to accumulate on the surface, as under virgin or forest conditions. Where annual crops are grown, the mulch and soil are disturbed and much of the mulch is mixed each year with the surface 2–6 inches of soil. In either case, the plant residues exert the various physical, chemical and biological effects that are so beneficial to growth of plants; i.e., they accelerate the rate of formation of good, highly-valued topsoil.

MULCHING MATERIALS

Mulching materials consisting of various kinds of plant materials have long been used by gardeners, fruit growers, nurserymen, and those interested in ornamental shrubs and flowering plants. These materials commonly include such materials as peat, manures, straw, cornstalks, corncobs, sugar-cane trash, leaves, peanut hulls, wood products, and various other kinds of litter. Since such materials must be applied to a depth of at least two inches if weeds are to be kept under control, it is obvious that they are too expensive (at least in terms of labor) for use as full mulches on field crops.

Sawdusts from various species of trees are often available in quantity for use in flower and vegetable gardens. Some of the practical aspects of the use of these wood products are considered by Allison and Anderson (1951), White et al. (1959), and Allison (1965), and in Chapter 21 of this book.

Other materials that have been used as mulches in gardens, and in a limited way on special crops, include paper, petroleum (Takatori et al., 1964), granular coke (Quashu and Evans, 1967), woodfiber cellulose (Barkley et al., 1965) and clear and colored plastics (Waggoner et al., 1960; Free and Bay, 1965). Considerable experimental work is now being done with these and other materials to determine their effects on soil moisture and temperature, and the resulting effects on early growth and final yields. They are also used to aid in establishing grass on roadbanks, fills, terraces and other recently-exposed soils. A cloth netting that permits seedlings to grow through the meshes is also very effective for this purpose if adequate nutrients and water are supplied. The use of these manufactured products will probably be confined to limited areas, or to special crops where early spring growth is essential, and where the money returns per acre are high.

When land is left undisturbed it quickly becomes well mulched with grass, weeds and shrubs, and eventually a forest with heavy leaf covering may represent the climax vegetation. Even stones and gravel on the surface act as effective mulches, and have been used in a limited way for many centuries by gardeners. Whatever the type of covering, the effects are beneficial but to varying degrees. Soil moisture is maintained at a higher level if no growing and transpiring plants are present.

EFFECTS OF MULCHES

Mulches are used primarily to increase water infiltration, reduce evaporation, modify soil temperatures, control weeds, prevent evaporation, and increase crop yields. They also increase the biological activities in the soil, modify the level of available nutrients, and help to maintain or increase the level of soil organic matter. Under conditions of no tillage, or minimum tillage of fine-textured soils, there is also likely to be a favorable effect on the physical conditions in the soil. These effects are discussed in the following pages.

Soil moisture

Mulched soils usually (Verma and Kohnke, 1951), but not always, supply more moisture to growing crops than do bare soils, or those that are cultivated frequently. All mulches serve to break the impact of the falling raindrop, usually increase the intake of water, and decrease the turbulent transfer of water vapor to the atmosphere (Lemon, 1956). The chief factors involved include the kind and depth of mulch, soil texture, amount and frequency of the rainfall, and amount of weed growth.

The effect of different amounts of straw used as a mulch under Great Plains fallow conditions is well illustrated by the data of Greb et al. (1967), shown in Table 25.I. In all

TABLE 25.I

SOIL WATER STORAGE BY SUMMER FALLOW*[1] AS AFFECTED BY WHEAT STRAW AT THREE GREAT PLAINS LOCATIONS (from GREB et al., 1967)

Location[2] *and years*	*Applied straw (kg/ha)*	*Water in soil (cm)*			*Fallow efficiency*[3] *(%)*
		initial	*end of fallow*	*net gain*	
Sidney, Mont.	0	3.8	9.4	5.6	16
2-year mean	1,680	3.5	10.1	6.6	19
	3,360	4.0	11.9	7.9	22
	6,720	4.0	13.9	9.9	28
Akron, Colo.	1,680	1.8	16.0	14.2	26
3-year mean	3,360	1.5	17.8	16.3	30
	6,720	·2.0	20.3	18.3	33
North Platte, Nebr.	3,360	2.8	21.8	19.0	29
4-year mean	6,720	4.3	24.6	20.3	31
	10,080	3.3	25.6	22.3	34

*[1] Fallow period of 14 months: July to second September each location.

*[2] Precipitation in cm during fallow period: Sidney, 35.5; Akron, 54.9; North Platte, 64.8.

*[3] Fallow efficiency % = $\frac{\text{Net gain soil water, cm}}{\text{Fallow pptn., cm}} \times 100$

cases there were gains in water storage as the amount of straw was increased. These gains were made primarily during the spring months. Under the heavier mulches over 70% of the net gains in water were found at depths below 61 cm of the soil profile where it would not be subject to appreciable evaporation losses. Average fallow efficiencies at the three locations were within the range of 22–32%.

The most desirable type of mulch is one that absorbs little moisture, does not pack or form a water-shedding type of surface, and allows the rainfall to move downward rapidly into the soil. Straws and wood chips are among the better mulching materials, whereas sawdusts, peats and manures are likely to pack too tightly and inhibit infiltration. The latter materials tend to absorb most of the rain that falls as light showers and speed its loss through capillarity. Artificial mulches consisting of paper, plastic, petroleum and metal sheets are likely to be effective if they are so used as to allow water to enter the soil readily. Lippert et al. (1964), for example, obtained moisture conservation by both petroleum and polyethylene mulches if the width of these materials was at least 6 inches. Bands 24 inches wide were superior to the 6-inch width. Stone mulches, although obviously not practical for most purposes, effectively conserve moisture by aiding infiltration and decreasing evaporation (Adams, 1965, 1966).

Very sandy soils are not likely to benefit appreciably by mulching except as the mulches control weeds. In such soils, infiltration is not a problem, and the soil surface dries quickly after each rain, forming a mulch that is not greatly different from that existing under a layer of stones. Capillarity is also not as marked a contributor to moisture loss as it is likely to be in fine-textured soils.

Wiegand et al. (1968) reported that a sand mulch 1.5 cm thick over a clay loam was slightly more effective than a cotton bur mulch in the retention of natural rainfall. This was true even though the average soil temperature under the sand was higher than under the bur mulch or bare soil.

There is now much evidence (Jacks et al., 1955; Rowe-Dutton, 1957; Army et al., 1961; and McCalla and Army, 1961) that mulches reduce evaporation when the soil just under the mulch is kept wet by frequent rains or otherwise, but has little or no effect when the upper soil dries out. An exception to this is where the mulch markedly increases infiltration initially, as it often does, with the corresponding increase in total moisture in the soil profile. Since soil moisture movement upward by capillarity is very limited, obviously the surface covering, whether an organic mulch, dust mulch or a hard bare surface, makes very little difference in moisture loss by evaporation after the initial drying out period. It is the water at the surface that got there by gravity and not by capillarity that is partially protected from evaporation by the mulch. The more frequent the showers, the more protection the mulch gives against evaporation, assuming that the mulch itself does not absorb and hold most of the water. During a prolonged dry period the mulch would not conserve much soil moisture; in regions or seasons of abundant rainfall the beneficial effect of the mulch is likely to be marked, and soil moisture is held more constant.

In the previous chapter it was pointed out that the dust mulch, formed by frequent cultivation, was at one time considered to be very effective in breaking capillarity and thereby preventing the escape of water from lower levels. We now know that such a soil mulch has little effect on the conservation of water because capillary movement upward in soil is very limited. Since even shallow cultivation is likely to break many feeding rootlets, and deprive the plant of the use of the upper two inches of fertile soil, the maintenance of a dust mulch may at times actually depress yields.

Soil temperature

The effect of mulches on soil temperature depends primarily upon the kind and depth of the mulch covering, the time of the year when the mulch is applied, and the light-reflecting and heat-absorbing properties of the mulch. In general, it can be stated that mulches keep the soil cooler during the summer months and warmer during the winter, but there are exceptions to this statement. Mulched soils usually show considerably less variation in temperature than do bare soils. A mulch applied in the late fall delays or prevents soil freezing, but if applied when the soil is frozen will tend to keep it frozen throughout the winter. Temperature differences due to mulching have often been shown to be as much as 4–8°C, and values twice these amounts have been reported (Jacks et al., 1955). The thicker the mulch layer the greater is the insulating effect.

In studies conducted in Texas, Adams (1965) found that the soil surface and mulch-soil interface temperatures were in the following order on fallow plots: bare > 1-inch gravel > 2-inch gravel > 2-inch straw. The daily soil temperatures at 1.30 p.m. from early June to mid-August varied from 90° to 95°F at a depth of 3 inches under bare soil, but were near 80°F under a 3-inch straw mulch.

Organic mulches, even though rather shallow, can sometimes retard seed germination in the early spring at the time that the sun's rays are beginning to warm the soil. The mulch that helps to prevent the escape of heat from the soil during the winter months also prevents the penetration of solar heat into the soil during the warmer months, especially where the mulch layer is thick. The latter factor, heat penetration, gradually outweighs the former as intensity of the sun's rays increases. Even with a comparatively light mulch of 1.5 tons of wheat straw per acre, Kohnke and Werkhoven (1963) observed that the germination of corn was 2 weeks later in mulched than in bare soil. Willis et al. (1957) concluded that "lower soil temperatures created by a mulch tillage system might well be a major reason for the poor early growth and the lower yields of corn that often occur with such a system in the central Iowa region". Such effects on yields do not seem to occur in the more southern states. The studies of Van Wijk et al. (1959) and of Walker (1969) support the conclusion of Willis et al.

The color of a mulch is an important factor in daily temperature variations during periods of intense illumination. Dark-colored mulches, such as black paper, polyethylene, and bituminous emulsions, absorb the heat and raise the soil temperature during the middle of the day (Collis-George et al., 1963; Courter and Oebker, 1964). Mulches that reflect the light produce temperatures more nearly like those in the unmulched soil. Experimental results with paper and plastic mulches sometimes give inconsistent and unexpected results because factors other than heat absorption and insulation are involved. These include such matters as their effects on moisture infiltration and moisture entrapment under sheets of mulching materials. Local conditions of air temperature, rainfall and season of the year are likely to play major roles in the results obtained with paper and plastic mulches. Under some conditions striking results have been secured with respect to speeding up early plant growth, even though the economics of the practice may be unfavorable for use with most crops (Miller and Bunger, 1963; Doss et al., 1966).

The fact that plant residue mulches have been shown to retard early germination and seedling development, as in Iowa, whereas plastic and paper mulches have been used in other areas to hasten plant growth in the early spring, emphasizes that general statements must be made with great caution. It is seldom safe to group all mulches together, for natural organic mulches commonly behave very differently from paper and plastic sheet mulches. And even these artificial mulches produce different effects if the color and temperature differ, and if used in different ways on different crops and under different climatic conditions.

Nielsen and Humphries (1966) summarized the recent work that deals with the effects of root temperature on plants and pointed out that our knowledge is woefully incomplete. The optimum for root growth is usually less than for tops, and the roots tolerate a narrower range of temperature than do the tops. This optimum temperature changes with age and season, and also depends on the shoot temperature.

Weed control

One of the most important advantages of mulches is their suppression of weeds, thereby eliminating cultivation. This benefit is of somewhat less importance now than formerly, since herbicides offer an alternate method of weed suppression. But mulches deep enough to control weeds are more often used in vegetable and flower gardens where herbicides are sometimes hazardous to use.

Most natural mulches must be applied at a depth after packing of at least two inches, and preferably four inches, to be effective in weed control. Since plant residue mulches are usually not effective on perennial weeds, and on many grasses, these must be eliminated before application. Nearly all annual weed seedlings are unable to grow through a thick mulch even if they are able to germinate. The supply of energy-yielding materials in the seeds is too small to permit much growth in the absence of light.

Some natural mulching materials are not very satisfactory in weed control, either because they pack tightly and serve as a good medium for germination and growth, or because the mulching materials themselves are contaminated with weed seeds.

Most of the artificial mulching materials, such as black paper or plastics, and aluminum foil, are satisfactory for weed control provided the soil is completely covered. If applied as perforated sheets, or in strips, some annual weeds will usually grow through the holes or cracks.

Soil organisms

Soils that are naturally mulched with tree leaves, grass sods, and miscellaneous types of plant debris are likely to be abundantly supplied with earthworms, provided the soil is not too acid or too dry. The same is true in gardens that are mulched with plant residues. One of the main reasons that they find living conditions so satisfactory is that the mulches commonly furnish them with an abundant supply of food. Furthermore, the worms find the physical conditions in the soil to their liking, just as do most plants. Even if the mulch itself is not a satisfactory food source, the plants living there furnish a continuous supply. Lack of disturbance of the soil also favors a high earthworm population; channels that they make through the soil profile may remain intact for one or more seasons. Mulches also keep the soil at a more uniform temperature and protect it from freezing, which is so detrimental to earthworm populations. In short, the many benefits, outlined in Chapter 4, that are derived from earthworm activities tend to reach a near maximum in soils that are kept mulched with plant debris. A grass sod is an ideal place for a high worm population.

Under Nebraska conditions, Teotia et al. (1950) observed a two- to five-fold increase in numbers of earthworms in stubble-mulched soil over plowed soil. On straw-mulched plots earthworms increased with the rate of straw application up to the maximum application of 8 tons per acre.

There is little evidence as to the effect of manufactured materials on earthworm populations. These materials would usually help to hold the soil moisture and maintain good physical conditions, but a more or less complete covering with sheets of paper, plastic, aluminum, or bitumen would doubtless not be conducive to worm activity. Most, or at least many of the species come to the surface of the soil to feed, and certainly sheets or strips of these materials should act as inhibitors. Perforated materials should be a little less suppressive.

Mulches of plant materials also favor the growth of other forms of animal life, some of which are beneficial and some harmful, but the overall effect on crop production is not likely to be marked. Harmful insects and some diseases may, however, find the natural mulches to their liking, but this is usually a comparatively minor factor in crop production.

The activities of soil microorganisms are also favorably affected by mulches of plant materials. This is due in part to the higher moisture and temperatures that prevail for much of the time during the year, but more especially to the abundant energy supply that is always available. During periods of frequent showers there is likely to be a heavy growth of bacteria, fungi and actinomycetes in the mulch layer but the increased growth is not limited to the mulch. Some of the energy-yielding materials are leached into the soil during each rain, and as the mulch decomposes the insoluble materials accumulate on or in the surface layer of the soil. Furthermore, earthworms are continually carrying the undecomposed plant materials into the soil. This of course favors marked increases in soil microorganisms but also speeds up the disappearance of the mulch itself.

Available nutrients

The effect of natural mulches on the amount of nutrients that are available to plants growing on the soil depends primarily on the composition of the mulches, and secondarily on the rate at which the mulches are decomposed. This statement is obvious since eventually the mulch, or the breakdown products that do not escape to the air, reach the soil. What products, and how much of them, are involved, and how soon they get into the soil, determine the end result.

Nitrogen is the most critical, and sometimes unpredictable, element involved. Whether a mulch will increase or decrease available nitrogen in the soil beneath the mulch depends upon the carbon–nitrogen ratio of the mulching material, and its ease of decomposition – especially its lignin content. For most crop residues the critical ratio is usually about 30 (N content 1.4–1.7), as explained in Chapter 6. The wider the ratio the more tightly the nitrogen is held by the decaying residues. The carbon and nitrogen contents, as well as carbon–nitrogen ratios, of several typical organic mulches, as reported by Bollen (1953), are shown in Table 25.II.

Nitrogen-deficient crop residues, used as mulches, commonly decrease the available nitrogen level in the soil and hence may depress the growth of any plants growing on the mulched area unless supplemental nitrogen is applied (Carpenter and Watson, 1954). The inhibition may be less than if the mulching materials were incorporated into the soil

TABLE 25.II

COMPOSITION OF ORGANIC MULCHING AND WASTE MATERIALS (WATER-FREE BASIS) (from BOLLEN, 1953)

Material	*Ash (%)*	*Carbon (%)*	*Nitrogen (%)*	*C/N*
Alfalfa hay	8.79	43.15	2.34	18
Bent grass clippings	17.98	43.22	3.23	13
Fiber flax, deseeded	3.73	44.70	0.12	373
Pea vines, in bloom	10.71	45.30	2.69	17
Pea vines, mature (less pods)	8.50	44.02	1.50	29
Meadow hay (rush and sedge)	8.46	45.60	1.07	43
Rye straw	3.51	47.39	0.33	144
Wheat straw	8.54	44.70	0.12	373
Oak leaves, weathered	32.33	35.11	1.36	26
Walnut leaves, weathered	43.42	29.48	1.12	26
Corn cobs	1.58	46.87	0.45	108
Rice hulls	19.83	39.80	0.55	72
Douglas fir needles	7.02	55.75	0.96	58
Douglas fir bark	0.45	53.97	0.11	491
Douglas fir sap wood	0.27	49.36	0.09	548
Douglas fir cones	1.51	49.17	0.37	133
Douglas fir sawdust, fresh	0.17	49.80	0.05	996
Red alder sawdust	1.21	49.63	0.37	134
Western red cedar sawdust	0.29	51.05	0.07	729
Ponderosa pine sawdust	0.33	53.18	0.05	1064
Moss peat	3.12	48.29	0.83	58
Sewage sludge, digested	53.65	22.00	2.15	10
Cannery waste, beans	–	31.47	3.17	10
Cannery waste, beets	–	42.85	2.32	18
Cannery waste, peaches	–	46.43	1.15	40
Cannery waste, pears	–	32.69	0.52	63

because the rate of decay is likely to be less. However, if rains occur frequently the difference may not be great, because the decomposition rate in a moist mulch is likely to be rather rapid, and the rains carry an appreciable amount of soluble carbohydrates into the soil. The portion of the mulch that is in contact with soil is subject to rapid decomposition, and the microorganisms involved remove most of the available nitrogen from the nearby soil.

Mulches consisting of sawdusts that decompose rapidly (see Allison, 1965 and Table 21.III) are good examples of those that should not be used without supplemental nitrogen. They are so nitrogen-deficient that very marked injury to crops can occur rapidly during warm weather. Sawdusts made from wood species that are very resistant to decay require only a small amount of nitrogen to offset any nitrogen-depleting effects.

Under tropical conditions, Vicente-Chandler (1953) states that the right kind of mulch, properly handled, can provide an economical and continuous supply of nitrogen for plants under conditions of high rainfall. This would be especially true where the mulch is renewed annually. Even mulches with carbon–nitrogen ratios above the critical ratio would supply some available nitrogen where the materials rot very rapidly as under moist tropical conditions. The mat of growing roots normally found under such a mulch would absorb a considerable portion of the available nitrogen and other nutrients before they could be removed by torrential rains. Soluble fertilizer nitrogen under such conditions would not long remain in the root zone.

Most nitrogen-deficient mulches are also phosphorus-deficient and may require small applications of phosphate fertilizers as well as nitrogenous fertilizers. The likelihood that mulches may deplete phosphates is, however, less than in the case of nitrogen.

The needs of the microorganisms that decompose mulches for the other major and minor elements are so small that there is little chance that a natural mulch will cause a deficiency of these. As soon as a mulch of plant materials is applied, and even before much decomposition has occurred, these mineral elements are subject to slow leaching with each rain. As decomposition proceeds, more and more of these elements are likely to move down into the root zone. If the mulch is not removed, the residual matter ultimately becomes a part of the soil, and all of the major and minor elements originally in the mulch are subject to assimilation by the crop.

The effects of artificial mulches, including aluminum, plastic, paper, wood pulp and bitumen, on available soil nutrients should be minor since they do not add appreciable amounts of mineral or organic nutrients. Any effects that they might have would be largely on soil moisture and temperature, which might either increase or decrease microbial activities in the soil. If these mulches increase plant growth, there would likely be an increase in the rhizosphere population, but this would have little effect on available soil nutrients.

Soil organic matter

Soils that are covered with mulches that are deep enough to prevent weed growth, and are not cultivated for long periods of time, retain their organic matter content much better than do cultivated soils. The absence of cultivation is partly responsible for this, but if the soil temperature is kept lower during the summer months this is also a factor. Fewer wetting and drying cycles likewise have a favorable effect on organic matter maintenance.

The main effect of organic mulches on humus maintenance is derived from the addition of the organic matter, assuming that the mulch is not removed at intervals. Under systems where the soil is kept mulched, and the mulch is replenished yearly, the beneficial effect is very marked. It is also marked if the old mulch is incorporated into the soil each spring or fall, followed by a yearly replacement of fresh mulching materials. In the first case mentioned the upper one or two inches of soil can become very high in organic matter; in the second case the entire plowed or disced layer benefits from the added carbonaceous materials. Which one of the two systems is the better is a moot question, and the answer depends largely upon the crop grown and the main purpose of the mulch. Certainly the tendency in recent years is to avoid the stirring of the soil any more than is absolutely essential.

Under virgin conditions, where soils were left undisturbed for centuries, two radically different types of soil profiles commonly developed. One was in the humid forested region where the typical podzol formed. The other was under grass where chernozems developed (see Chapter 7). Conditions in soils that are mulched artificially with plant materials are very different from those existing in either podzols or chernozems. The results obtained are also different but, hopefully, can be made to be more like the chernozem in the plowed layer, at least.

Soil physical properties

Soils of medium or fine texture that are cropped and kept mulched with plant-residue mulches and stirred infrequently or not at all, usually have or develop excellent physical qualities. The structure or aggregation of such soils does not suffer compaction from heavy machinery or aggregate disruption due to tillage, and to wetting and drying.

As the organic mulch decomposes, a small portion of the disintegration products and the synthetic products of microorganisms are leached into the soil. Earthworms are even a more important factor. The channels made by them tend to decrease bulk density and increase aeration and drainage. The longer an organic mulch remains on the soil the more it tends to assume the characteristics of a virgin soil, and many of these represent the ultimate in good physical condition. Such a mulched soil has a high infiltration rate, and furthermore tends to hold the water until it has time to move down into the profile. Good physical properties also favor water retention in the profile until the crop can utilize it.

There is universal agreement that organic matter favors good soil tilth, but how effective is the organic matter when applied as a mulch? Would crop residues be more effective if they were mixed intimately with the soil instead of being allowed to decay on the surface? A few years ago most soil scientists would have given a positive answer to this last question, but now there seems to be less agreement as to the answer. This is because more recent data seem to show that residues that are mixed with uncropped soils, at least under laboratory conditions, usually produce only temporary increases in aggregation. Physical factors, such as growing roots, wetting and drying, and freezing and thawing seem to be of first importance in aggregate formation; products of microbial action help to hold the clay particles in close proximity after the aggregates are formed by other agencies, but are of minor importance alone as aggregate formers (see Chapter 16). If further work supports this viewpoint, then organic matter left on the soil surface may be as valuable in aggregate formation as if it were thoroughly mixed with the soil; it might be even more valuable. The products that are leached into the soil from the decaying mulch probably furnish all of the polysaccharides and related substances needed for use as aggregate cements. The mass of growing roots serve as aggregate formers.

Root growth

Organic mulches favor the growth of more extensive plant root systems, because these mulches usually favor higher moisture levels, more uniform temperatures, and better physical conditions in the soil (Vicente-Chandler, 1953). The growth of the roots of many plants is markedly inhibited by soil temperatures above about 28–30°C. A thick layer of plant residue usually keeps the soil cooler during the summer months and may also reduce the depth of freezing during the winter. Good physical conditions of soil under mulches, and low bulk density, also favor root proliferation and penetration to lower depths. One very important result of the increased number and length of the roots is that more of the total moisture in the soil is made available for crop production.

An effective mulch also makes possible the extensive growth of plant roots in the upper one or two inches of soil, and sometimes even into the mulch itself. This portion of the soil profile is likely to be the most fertile, and if the mulch permits the crop to use this surface layer as a growth medium an increase in crop can be expected. If the mulch completely controls weeds, then the crop is not subject to competition and its roots can make full use of all of the soil.

Soil erosion

Mulches of plant materials that are not readily carried away by running water are very effective in the prevention of erosion. This statement is obvious from what has been said, since mulches absorb the energy of the falling raindrop, improve infiltration, allow less water to run off and improve the physical condition of the soil (Adams, 1965, 1966). Very heavy rains may occasionally carry away some of the mulching material and produce gullies, but this effect is not usually encountered if there is a crop on the soil that covers most of the area. Light-weight materials, such as sawdust and peat, may be floated away at times as gullies form but fibrous materials are less likely to be displaced (see Chapter 27).

In simulated rainfall experiments Mannering and Meyer (1963) observed that wheat straw applied at rates of 1, 2 and 4 tons per acre maintained very high infiltration rates with essentially no erosion; in contrast, unmulched soils lost 12 tons of soil per acre. Even a one-fourth-ton application of straw reduced the soil loss to three tons per acre. The straw mulch obviously reduced surface sealing and decreased rainfall and runoff energy.

Natural mulches as found in forests, waste lands and grasslands are especially effective in erosion control. Mulches of artificial materials are also usually effective if they are sufficiently anchored and allow moisture to enter the soil readily.

Crop yields

The effects of mulches on yields of annual crops are nearly always beneficial since they usually make the soil a better medium for plant growth and also control weeds.

Some of the practical aspects of mulching in the growing of vegetables, and some of the yield data that have been reported, are discussed by Rowe-Dutton (1957).

In a 3-year study in Virginia, Moody et al. (1963) grew corn on plots that received 3 tons of wheat straw per acre, either plowed under or placed on the surface, with two rates of applied nitrogen. Yields are given in Table 25.III. Mulched corn produced 42 bushels per acre more grain than where the straw was plowed down. This unusually large yield increase was attributed primarily to the greater moisture under mulch during the period of high plant requirements. The mulch decreased soil temperatures and depressed early growth, but summer growth was greatly stimulated. Runoff was seven times greater from the unmulched plots.

TABLE 25.III

CORN YIELDS AS INFLUENCED BY SURFACE AND PLOWED-UNDER STRAW WITH TWO RATES OF NITROGEN FERTILIZER (from MOODY et al., 1963)

Straw placement (3 tons/acre)	*Nitrogen (lb./acre)*	*Grain yields (bushels/acre)*			
		1958	*1959*	*1960*	*average*
Plowed under	75	81.5	52.8	54.6	63.0
Surface mulch	75	109.3	121.6	94.2	108.4
Plowed under	175	82.3	48.9	50.1	60.4
Surface mulch	175	101.0	126.6	72.6	100.1

Mulches are apparently less likely to increase the yields of tree crops and other deep-rooted perennials than of annuals. Cahoon et al. (1961), for example, state that in citrus orchards the overall benefit to yields and tree conditions from the application of 4 inches of wood shavings for 5 years was nil; only in one of these orchards, where water infiltration was a problem, did the mulch improve tree condition.

One benefit of mulches, seldom mentioned, is derived from the additional carbon dioxide that is constantly being liberated as they decompose. A small but unknown part of this carbon dioxide is absorbed by the plant roots, and another portion is taken up by the leaves, especially by those that are located near the soil surface. The amount absorbed tends to increase as the density of the vegetation increases, since a heavy plant canopy retards the rate of escape of the gas to the air above the growing crop.

Unfavorable effects of mulches, occasionally observed, are most likely to result from deficiencies of nitrogen, and sometimes of phosphorus, that may occur under mulches of materials of wide carbon–nitrogen ratios. Mulches may also be a source of phytotoxic substances naturally present or synthesized by certain microorganisms that are active in their decomposition (see Chapter 18).

Sometimes unfavorable effects may be experienced in very rainy seasons, or on low, poorly-drained soils. In such cases the soil may be kept too wet or cold, and this in turn may result in damage from disease organisms. Heavy mulches that pack around plants may sometimes favor root rots.

The benefits of mulches on annual crops generally far outweigh any likely harmful effects, but the economics of mulching are likely to be very unfavorable.

Considerable interest has been shown in recent years in the effect of manufactured materials, used as mulches, on early plant response and yields. The work of Bennett et al. (1966) serves as a good example. In field studies with cotton, abundantly fertilized, and with irrigation as a variable, they found that black plastic mulch increased seed cotton yields by 650–975 lb. per acre with or without irrigation. Irrigation, alone, increased seed cotton production by more than 1,600 lb. per acre both in the presence and absence of the mulch. The plastic mulch accelerated early growth and fruiting, reduced rate of soil moisture loss, increased early season minimum soil temperature, and gave satisfactory control of weeds without cultivation.

STUBBLE MULCHES

Stubble-mulch or trash-mulch farming is a practice that was initiated during the period of 1930 to 1940 in the semi-arid and wheat-growing areas of the United States and Canada (Duley and Russel, 1948; Free, 1953; Jacks et al., 1955; Daniel et al., 1956; Zing and Whitfield, 1957; Norstadt and McCalla, 1960; Larson and Beale, 1961; McCalla and Army, 1961; Horning and Oveson, 1962; Ramig and Mazurak, 1964). The system was developed as a result of the extremely severe wind erosion that occurred at this time, and represented a major attempt to curtail as much of this damage as possible. The wind damage in the 1930s was unusually bad because of the severe drought that occurred shortly after much of the land that had long been in native grasses was put under cultivation.

Stubble-mulch farming is commonly defined (McCalla and Army, 1961; Horning and Oveson, 1962) as a year-round way of managing plant residues on cropland in which harvesting, cultivating, seedbed preparation, and planting are performed in such a way as to leave the residues of the previous crop on top of or near the soil surface.

Residues left on the soil surface decompose at a slower rate than when they are buried, and under some conditions considerable residue may remain from one season to the next (Brown and Dickey, 1970). This is of course very desirable in a stubble-mulch system of farming. Such resistance to decay is dependent upon the kind of residue, temperature, moisture relations, and extent of soil disturbance during the tillage operations.

Composition and amount of residues

The nutrient content of unharvested or ungrazed parts of plants above the ground that are usually returned to the soil, as given by Larson and Beale (1961), are shown in Table 25.IV. These values are approximate averages for plants at harvest time. They point out that many factors, such as soil, fertility, weather and stage of maturity influence the nutrient content of crops. According to Larson and Beale, plants grown under normal

TABLE 25.IV

NUTRIENT CONTENT PER TON OF UNHARVESTED OR UNGRAZED PARTS OF PLANTS ABOVE THE GROUND USUALLY RETURNED TO THE SOIL (from LARSON and BEALE, 1961)

Crop	*Nitrogen (N) in lb.*	*Phosphorus (P_2O_5) in lb.*	*Potash (K_2O) in lb.*
Barley	12	5	29
Oat	12	4	30
Rye	10	6	17
Wheat	14	3	23
Corn	18	8	20
Cotton	22	7	35
Soybean	12	9	25
Grasses	40	4	43
Alfalfa	48	11	45
Red clover	38	9	35
Sweet clover	36	9	33
Cowpea	62	12	45
Vetch	62	14	46
Ladino clover	60	13	60
Lespedeza	42	10	20
Fescuegrass–Ladino clover	61	17	62
Ryegrass–crimson clover	60	13	61

conditions with adequate nutrients will produce residues in the following ranges: barley straw, 1–2 tons; oat straw, 1.5–2 tons; wheat straw, 1.5–2.5 tons; corn stover, 2–4 tons; and soybean leaves and stems, 1.5–2.5 tons per acre. In addition, roots contribute considerable plant material and nutrients that affect plant growth through the release or tie-up of plant nutrients. These roots are usually more resistant to decay and lower in nitrogen than are the above-ground residues.

Equipment and tillage

Various types of machinery are used in the stubble-mulch system of farming, depending on the crop grown, soil, climate, amount and type of residue, and local conditions. Carter and McDole (1942), Duley and Russel (1948), Jacks et al. (1955), Horning and Oveson (1962), and many others have described the leading types of equipment used. Of course not all of this equipment is suitable for use in any one farming operation.

Jacks et al. (1955) list the three types of tillage equipment used for initial tillage and sowing as subsurface, soil-churning, and soil-turning implements. The subsurface implements, which are the most important in stubble mulching, include sweeps or blade weeders, duckfoot cultivator, straight-blade weeders, lister bottom plow, modified moldboard plow, spring-tooth plow, rod weeder, and field cultivator. They list the secondary tillage implements as modified initial-tillage implements, tredder or treader, packer seed drills, stubble pulverizers and rotary subsoilers. They describe and discuss at some length the use, suitability and merits of these various types of equipment.

Tillage operations in connection with the stubble-mulch system are ordinarily kept to the minimum necessary to prepare a suitable seedbed, and to keep weeds under control. Usually the sweep or blade is used for lifting the soil initially and killing the weeds. It operates at depths of up to six inches with subsequent tillages with various implements at lesser depths. Draft requirements for the sweep cultivator are usually about 70–80% as great as for the moldboard plow operating at the same depth.

The stubble-mulch system is especially suited for the maintenance of summer fallows and for the culture of small grain crops. In either case the equipment used should not only leave essentially all of the crop residues on the surface, but it is also important that these residues be uniformly distributed. This farming system can also be used for the growing of row crops, such as corn or sorghum. In this case the seed is placed in a clean furrow with the residues covering the area between the rows. Either a lister operated at shallow depth, or a planter equipped with a furrow opener, may be used to facilitate seeding. Cultivation may be done with sweeps or other equipment that undercut the residues. Often the control of weeds, particularly of grasses, is difficult, and more cultivations may be necessary than would otherwise be considered desirable. In the case of sods, it is sometimes necessary to use the moldboard plow to bring about inversion, followed later by the use of a spring-tooth harrow to bring some of the residues to the surface. Herbicides are now being used to some extent, but not extensively for both scientific and economic reasons.

Wind erosion control

Residues that are anchored to the soil are very effective in the reduction of wind erosion, except where the amount present is very limited, or where they are largely buried or much decomposed. Wheat stubble is more effective than cornstalks or sorghum residues, and is more effective when standing than when flattened. This is attributable in part to the greater resistance of a soil that is so covered but, more important, the stubble protects the soil from the wind; in other words the wheat stubble slows down wind velocity. As little as 500–1000 lb. per acre may give fairly good protection for medium-textured soils, but twice this amount is required for coarse-textured soils and clays. Twice these amounts of corn residues may be required since they usually lie flat on the ground and cover a smaller percentage of the soil. Fineness, height, density and orientation of residues are all important in protection against the wind.

Drullinger and Schmidt (1968) call attention to the wind erosion problem in the Great Lakes states on soils having surface textures of very fine sand, loamy sand or sandy loam with too little clay or organic matter to form wind-resistant soil structures. Cultivated peats and mucks are also problem soils. Various systems of minimum tillage that keep crop residues on the surface are being used successfully for erosion control. Where the residues are inadequate, oats are sometimes seeded as a fall cover crop. When winter-killed, the plants serve as an excellent protective cover. There is also increasing interest in no-tillage corn culture, using herbicides for weed control.

Among the chief soil factors that tend to limit wind erosion are soil aggregation, water-stability, soil moisture and nature of the soil surface. The portion of the colloidal organic matter that helps to bind the clay into comparatively large stable aggregates serves to decrease wind erosion. On the other hand, loose, light-weight organic matter that is largely detached from the soil may be blown away readily if it lies on the surface. Dead or living grass sods serve as excellent protectors of the soil against winds of high velocity (see Chapter 27).

Water infiltration and erosion

Any covering of a soil with living or dead organic matter protects it against water erosion (Beale et al., 1955; Army et al., 1961). This is partly the result of protection against the force of the rain which acts to shatter aggregates, as discussed in Chapter 27. In addition, the plant residues or other cover that are anchored to the soil act as retarders of water movement and thus give more time for infiltration to occur. The extent to which residues increase infiltration depends upon many factors but especially on soil texture, organic matter content and physical condition. Stubble-mulched soils usually provide more water for the growing crop than bare soils, and much of the difference is attributable to greater infiltration rather than to decreased evaporation brought about by the mulch.

Comparisons of stubble mulch with complete chemical fallow systems of farming have usually given results that favor the former system. For example, Black and Power (1965) reported that wheat yields on stubble-mulched soils were higher than where spray was used. Furthermore, neither chemical fallow nor combinations of chemical and mechanically-tilled plots resulted in more moisture conservation than with conventional stubble mulch. Wind erodibility was, however, less with complete chemical fallow soils, doubtless because of complete absence of tillage.

Burwell et al. (1968) in their discussion of the effect of tillage on water intake state that "fall mulch-tilled surfaces provided 8 times greater infiltration capacity before runoff started and 4 times greater infiltration during runoff the following spring than did fall plowed surfaces disked and harrowed in the spring. Spring infiltration for fall mulch-tilled surfaces was about 3 times greater than for spring plowed surfaces, both before and after runoff started. These tillage-infiltration relationships emphasize the need to use crop residues as surface mulches on sloping cropland where traditional tillage practices limit rainfall infiltration in the early part of the crop season when runoff and erosion are most likely to occur."

The factors influencing water erosion, according to McCalla and Army (1961), are chiefly intensity, amount and duration of rainfall; amount and velocity of surface flow; nature of the soil and its cover; and slope of the land. Organic matter in the form of residues on the surface are more effective in erosion prevention than are buried residues, or thoroughly decomposed organic matter that is a part of the soil mass.

Stubble mulching with adequate amounts of plant materials can markedly reduce water erosion, but will seldom completely prevent it during showers of high intensity, especially on clay or loam soils. The greater the slope, the more need for other means of erosion control such as terracing, strip cropping, and the use of grasses or other types of more or less permanent plant cover. Any of these practices that slow down water movement not only tends to keep the soil in place but increases water-use efficiency and crop yields under conditions where the rainfall is a limiting factor.

Evaporation losses

The main benefits from leaving crop residues on the surface are in the reduction of wind and water erosion; their effects on evaporation are usually minor. When rain falls at comparatively short intervals, mulches of plant residues retard loss by evaporation for a time, but after the surface moisture has disappeared the stubble-mulched soils lose moisture about as fast as a bare soil. This is true chiefly because there is little movement of water by capillarity from the deeper horizons. The extra retention of surface moisture, even if temporary, is often beneficial to seed germination and also to increased infiltration and downward movement of rainfall.

The above statements are illustrated in part by the studies of Greb (1966). He observed that wheat straw applied to the soil surface at rates of 1,120, 2,240 and 3,360 kg/ha, equivalent to 30, 60 and 90% coverage, reduced water losses from a wet soil surface by evaporation 16, 33 and 49%, respectively, during a 20-day period compared with no straw. An application of 6,720 kg/ha, or 180% soil coverage, was only slightly more effective than the 3,360 kg/ha application. As the soil water was evaporated the effectiveness of the mulches diminished.

Studies reported by Army et al. (1961) showed that the soil moisture content below 2 inches was not materially increased by surface residues. Evaporation losses during the summer months from both stubble-mulched and bare fallow soils constitute a high percentage of the total precipitation. A summary of many experiments conducted in the Great Plains showed losses during the fallow period of 76% of the precipitation. In other tests 83% of the rainfall was lost between the harvest of one crop and the seeding of the next (Mathews and Army, 1960).

Climate as a factor

The system of leaving the crop residues on the soil surface, which developed in the Great Plains and in the Pacific Northwest, did not initially spread to the more humid regions, primarily because of the weed problem. In the humid regions many of the more pestiferous weeds that were undercut by sweeps were only retarded and resumed their growth after the next rain. The development of suitable herbicides in recent years has partly overcome the weed problem, and there is now an increasing tendency for farmers to try various stubble-mulch or minimum tillage systems. The abundance of comparatively cheap nitrogen fertilizers is also accelerating this tendency.

Bondy (1968) reported that some farmers in central Kansas are successfully growing continuous wheat, grain sorghum and soybeans according to the stubble-mulch system even without the use of herbicides. The main purpose is to prevent wind and water erosion, but better infiltration also leads to more efficient use of the rainfall.

Minimum tillage practices and conventional tillage, conducted under suitable conditions for both, have usually given nearly equal yields. However, Van Doren Jr. and Ryder (1962) made 211 paired treatment tests on Ohio soils under various growing conditions and obtained a mean difference in yield of 4.8 bushels of corn per acre in favor of minimum tillage. Economically this gain is about as great as the savings in time and power usually ascribed to minimum tillage.

Another form of mulch or minimum tillage farming, reported by Stevens et al. (1968) from North Carolina, is sod planting in which corn, sorghum and other crops are planted in sod residues or living sods. If the sods are not killed with herbicides, the practice is usually used with grasses, such as fescue, orchardgrass or bluegrass, that have at least a partly dormant period when the corn is making its maximum growth. The seed are drilled in a narrow band that is opened up by means of various types of tillage implements. Adequate fertilizer and moisture are essential for success with sod planting. Savings in labor costs can be substantial.

REFERENCES

Adams, J.E., 1965. *Agron. J.*, 57: 471–474.

Adams, J.E., 1966. *Soil Sci. Soc. Am., Proc.*, 30: 110–114.

Allison, F.E., 1965. *U.S. Dep. Agric. Tech. Bull.*, 1332: 1–58.

Allison, F.E. and Anderson, M.S., 1951. *U.S. Dep. Agric. Circ.*, 891: 1–19.

Army, T.J., Wiese, A.F. and Hanks, R.J., 1961. *Soil Sci. Soc. Am., Proc.*, 25: 410–413.

Barkley, D.G., Blazer, R.E. and Schmidt, R.E., 1965. *Agron. J.*, 57: 189–192.

Beale, O.W., Nutt, G.B. and Peele, T.C., 1955. *Soil Sci. Soc. Am., Proc.*, 19: 244–247.

Bennett, O.L., Ashley, D.A. and Doss, B.D., 1966. *Agron. J.*, 58: 57–60.

Black, A.L. and Power, J.F., 1965. *Soil Sci. Soc. Am., Proc.*, 29: 465–468.

Bollen, W.B., 1953. *J. Agric. Food Chem.*, 1: 379–381.

Bondy, E.J., 1968. *Soil Conserv.*, 33: 255–256.

Brown, P.L. and Dickey, D.D., 1970. *Soil Sci. Soc. Am., Proc.*, 34: 118–121.

Burwell, R.E., Sloneker, L.L. and Nelson, W.W., 1968. *J. Soil Water Conserv.*, 23: 185–187.

Cahoon, G.A., Stolzy, L.H. and Morton, E.S., 1961. *Soil Sci.*, 92: 202–206.

Carpenter, W.J. and Watson, D.P., 1954. *Soil Sci.*, 78: 225–229.

Carter, L.S. and McDole, G.R., 1942. *U.S. Dep. Agric. Farmer's Bull.*, 1917: 1–24.

Collis-George, N., Davey, B.G., Scotter, D.R. and Williamson, D.R., 1963. *Aust. J. Agric. Res.*, 14: 1–11.

Courter, J.W. and Oebker, N.F., 1964. *Proc. Am. Soc. Hort. Sci.*, 85: 526–531.

Daniel, H., Cox, N.B. and Elwell, H.M., 1956. *U.S. Dep. Agric., Prod. Res. Rep.*, 6: 1–44.

Doss, B.D., Bennett, O.L. and Ashley, D.A., 1966. *J. Soil Water Conserv.*, 21: 99–101.

Drullinger, R.H. and Schmidt, B.L., 1968. *J. Soil Water Conserv.*, 23: 58–59.

Duley, F.L. and Russel, J.C., 1948. *U.S. Dep. Agric. Farmer's Bull.*, 1997: 1–32.

Free, G.R., 1953. *Soil Sci. Soc. Am., Proc.*, 17: 165–170.

Free, G.R. and Bay, C., 1965. *Soil Sci. Soc. Am., Proc.*, 29: 461–464.

Greb, B.W., 1966. *Soil Sci. Soc. Am., Proc.*, 30: 786–788.

Greb, B.W., Smika, D.E. and Black, A.L., 1967. *Soil Sci. Soc. Am., Proc.*, 31: 556–559.

Horning, T.R. and Oveson, M.M., 1962. *U.S. Dep. Agric. Inform. Bull.*, 253: 1–28.
Jacks, G.V., Brind, W.D. and Smith, R., 1955. *Commonwealth Bur. Soil Sci., Tech. Commun.*, 49: 1–87.
Kohnke, H. and Werkhoven, C.H., 1963. *Soil Sci. Soc. Am., Proc.*, 27: 13–17.
Larson, W.E. and Beale, O.W., 1961. *U.S. Dep. Agric. Farmer's Bull.*, 2155: 1–14.
Lemon, E.R., 1956. *Soil Sci. Soc. Am., Proc.*, 20: 120–125.
Lippert, L.F., Takatori, F.H. and Whiting, F.L., 1964. *Proc. Am. Soc. Hort. Sci.*, 85: 541–546.
McCalla, T.M. and Army, T.J., 1961. *Adv. Agron.*, 13: 125–196.
Mannering, J.V. and Meyer, L.D., 1963. *Soil Sci. Soc. Am., Proc.*, 27: 84–86.
Mathews, O.R. and Army, T.J., 1960. *Soil Sci. Soc. Am., Proc.*, 24: 414–418.
Miller, D.E. and Bunger, W.C., 1963. *Agron. J.*, 55: 417–419.
Moody, J.E., Jones Jr., J.N. and Lillard, J.H., 1963. *Soil Sci. Soc. Am., Proc.*, 27: 700–703.
Nielsen, K.F. and Humphries, E.C., 1966. *Soils Fert.*, 29: 1–7.
Norstadt, F.A. and McCalla, T.M., 1960. *Agron. J.*, 52: 477–479.
Quashu, H.K. and Evans, D.D., 1967. *Soil Sci. Soc. Am., Proc.*, 31: 429–435.
Ramig, R.E. and Mazurak, A.P., 1964. *Soil Sci. Soc. Am., Proc.*, 28: 554–557.
Rowe-Dutton, P., 1957. *Commonwealth Bur. Hort. Plantation Crops, Tech. Commun.*, 24: 1–169.
Stevens, W.W., Abernathy, C.C. and Pollock, J.E., 1968. *Soil Conserv.*, 33: 246–247.
Takatori, F.H., Lippert, L.F. and Whiting, F.L., 1964. *Proc. Am. Soc. Hort. Sci.*, 85: 532–540.
Teotia, S.P., Duley, F.L. and McCalla, T.M., 1950. *Nebr. Agric. Exper. Stn., Res. Bull.*, 165: 1–20.
Van Doren Jr., D.M. and Ryder, G.J., 1962. *Agron. J.*, 54: 447–450.
Van Wijk, W.R., Larson, W.E. and Burrows, W.C., 1959. *Soil Sci. Soc. Am., Proc.*, 23: 428–434.
Verma, A.B.S. and Kohnke, H., 1951. *Soil Sci.*, 72: 149–156.
Vicente-Chandler, J., 1953. *J. Soil Water Conserv.*, 8: 136–139, 144.
Waggoner, P.E., Miller, P.M. and De Rov, H.C., 1960. *Conn. Agric. Exper. Stn., New Haven, Bull.*, 634: 1–44.
Walker, J.M., 1969. *Soil Sci. Soc. Am. Proc.*, 33: 729–736.
White Jr., A.W., Giddens, J.E. and Morris, H.D., 1959. *Soil Sci. Soc. Am., Proc.*, 23: 365–368.
Wiegand, C.L., Heilman, M.D. and Swanson, W.A., 1968. *Soil Sci. Soc. Am., Proc.*, 32: 276–280.
Willis, W.O., Larson, W.E. and Kirkham, D., 1957. *Agron. J.*, 49: 323–328.
Zing, A.W. and Whitfield, C.J., 1957. *U. S. Dep. Agric. Tech. Bull.*, 1166: 1–56.

Chapter 26

GROWING CROPS ON SUBSOILS AND MINE SPOILS

INTRODUCTION

Topsoil is a valuable material, as every gardener knows. It is so valuable that laws have been passed in European countries requiring that when excavations are made, the surface soil must be removed carefully and be replaced after the operation is complete. This shows indirectly how comparatively less valuable is the subsoil for agricultural use. The various chapters of this book outline in considerable detail the many reasons for the high value placed on soil from the A-horizon. Most of these reasons center directly or indirectly on the presence of organic matter, much of it in colloidal form and in physical and chemical combination with the inorganic portion of it.

Many of our soils now have no true A-horizon. Most often this is because extensive erosion of cultivated areas over a period of many years has removed most of the topsoil. It is also the result of various kinds of building operations, including the construction of houses, railroads, highways, and various pipe lines. In many of our cultivated soils the plowed layer now consists of a mixture of remnants of the A-horizon, and of the underlying layer. Since the farming of subsoils is often a far more difficult operation than growing crops on the A-horizon, it is well to consider some of the problems involved and their possible solutions.

CHARACTERISTICS OF SUBSOILS

The term subsoil will not be used here in any very exact sense, but will refer to all of the layers below the A-horizon where plant roots commonly penetrate. The emphasis will be on the B-horizon, but not exclusively, for in actual agricultural practice it is seldom possible to study this horizon isolated from the others. A badly-eroded soil usually contains some A-horizon. Even where the B-horizon is exposed and crops are being grown on it, many of the plant roots may be in the C- and D-horizons and dependent upon these lower horizons for much of their nutrient supply and moisture. Furthermore, where extensive excavations or mining operations have been conducted the whole soil profile, including much parent material, is commonly mixed. The discussion here will, therefore, be concerned primarily with the growing of crops on soil or soil material that contains little or no A-horizon.

Subsoils differ greatly in properties, and their suitability for use in cropping differs correspondingly. They may be deep or shallow, and uniform or non-uniform. As stated by Winters and Simonson (1951), "subsoils range in texture from gravel to heavy clay, in reaction from very acid to strongly alkaline, in fertility from very low to very high, and in structure and consistence from granular and friable to blocky, hard and plastic, or even cemented". Obviously, few general statements can be made regarding their utilization in agriculture.

Reference was made in Chapter 20 to some of the chief characteristics of the main types of soil horizons. For further information on the nature of the subsoil materials, reference should be made to the excellent discussion by Winters and Simonson (1951). They give much information on the physical properties, clay minerals and fertility levels of the B-horizons of podzols, latosols, chernozems, and desert soils. They also discuss pan layers. In many cases where these pan layers exist they play a major role in crop production and present problems in addition to those generally encountered in farming subsoils.

GREENHOUSE VS FIELD STUDIES OF SUBSOILS

Before discussing problems encountered in the use of subsoils as plant growth media, it should be emphasized that studies connected with exposed subsoils left in place may give very different results than studies of the same subsoils in the greenhouse. In pot experiments it is very unusual to find a B-horizon soil that does not support good plant growth if available nutrients are added as needed, and any obvious inhibiting factors, such as acidity, are corrected. The same treatments given to an exposed subsoil in the field may give very unsatisfactory results. This usually signifies that physical factors in the field are often more important than chemical ones.

In greenhouse experiments it is common practice to dry and sieve the soil, add nutrients if desired, place the soil in a pot, and water at frequent intervals. The potting procedure increases oxidation and possibly available nutrients, but these effects do not adequately explain the better results obtained in the greenhouse. The physical conditions are often very different in the two types of experiments. In the field, such factors as poor aeration in a mass of clay soil, poor water infiltration and drainage, poor root development, and claypans or hardpans, may play a major role. In the carefully-conducted greenhouse experiment these factors are eliminated. Even if the soil is too compact for good root growth in the soil mass, this is likely to be comparatively unimportant because most of the roots in a greenhouse pot are found lining the pot and outside the soil mass. In this position, root aeration is good and the supply of available nutrients, if added, makes it unnecessary for the roots to penetrate into the soil mass to obtain them. In fact, the small mass of soil in the pot, together with continuous loss of water and careful watering, probably assure good aeration even in the center of the soil mass.

Growth on exposed banks or roadcuts is often so poor as to suggest to the inexperienced that toxicity is the dominant factor, at least for the first year, but this is seldom the case. A greenhouse experiment to which nutrients are added will usually demonstrate very quickly that factors other than toxic substances are involved.

SOME SUBSOIL CONDITIONS THAT AFFECT PLANT GROWTH

Subsoils vary widely in their ability to support plant growth. In some cases the addition of adequate nutrients will result in good crop growth. However, many other subsoils are problem soils and may support only a limited vegetative cover. Some of the reasons for the wide differences in plant response, mentioned in part above, are discussed in the following pages.

Infiltration and erosion

Exposed subsoils, especially if they are of fine texture and on a considerable slope, are likely to shed more water than infiltrates into them. The result is very excessive erosion and a droughty soil that may not be able to support any vegetation during hot, summer months. On roadbanks this problem is often partially solved by the addition to the surface of straw or other kinds of organic matter. It is also good practice to sow legumes and grasses to try to establish a vegetative cover as quickly, and as heavy, as possible. Trees may be set out or they may gradually take over the area if not disturbed. All of these practices tend to increase infiltration.

On fine-textured subsoils of moderate slope slow infiltration is also a problem, but a minor one compared to that on roadbanks. A cover of fertilized legumes and grasses, with little or no cultivation after the initial seeding, will also aid in the development of a subsoil into a productive one provided drainage is good and pan layers are absent. As the plant cover improves soil aggregation, and adds organic matter, infiltration is improved and erosion largely eliminated.

Needless to say, exposed sandy subsoils commonly present few problems with respect to infiltration. This is true even if the slope is as great as 10% or more.

Crust formation and seed germination

The development of surface crusts that are hard enough to greatly reduce infiltration and interfere with seed germination is of common occurrence in the finer-textured soils. Sometimes even silts and sands that have considerable clay may also become very compact. This is much more of a problem on exposed subsoils than on A-horizons because of the lower content of organic matter in the former. The crusts are not likely to interfere greatly with the emergence of seedlings of most field crops, but can be very damaging to the emergence of many garden and flower seedlings. A thin layer of peat or other suitable organic matter over the seedbed row will usually assure good seed germination and emergence. In very sandy soils, where crusts do not form, poor germination may sometimes occur because of limited moisture in the vicinity of the seed.

Aeration and moisture

There seems to be no doubt from the limited data available that one of the main problems in growing crops on exposed fine-textured subsoils is poor aeration in the soil mass. This condition is the result in many cases of poor aggregation and limited internal space available for the movement of air. In well-aggregated soil, air ordinarily moves freely in the large spaces between aggregates but of course such movement is impossible if no aggregates are present. In addition, the moisture that is tightly held in the soil may take the place of air. Water movement downward is very limited in such a soil; in fact, it behaves essentially as though it were a true claypan.

The roots of most plants require abundant oxygen for their metabolic processes and are not likely to enter a near-anaerobic environment. In oxygen-deficient soils plants do not grow normally, and any root extension is likely to be limited to cracks or open spaces where air and moisture are present. The problem here, like most of those involved in growth on exposed subsoils, is limited to soils of high clay content. In more open soils poor aeration could occur only in poorly-drained soils.

Aggregation

Poor aggregation in subsoils in comparison with surface soils is a general characteristic of these layers, but there are many exceptions. Fundamentally, lack of aggregation is commonly the result of deficient organic matter, high degree of compaction of the clay, and limited root growth, especially in the deeper layers of podzols. The leaching downward of organic matter, basic materials and clay in these soils not only leads to poor aggregation but these materials may be cemented into various types of dense formations. Even the organic matter that moves downward is seldom well distributed but precipitates in pan layers. Root extension is often curtailed and this in turn limits aggregation.

The deeper layers of chernozems usually have good physical properties although not as good as in the A-horizon. In these soils clays of the 2:1 type lattice predominate in the B-horizon and this leads to somewhat higher plasticity and lower friability than in the A-horizon. The nutrient supply is excellent and root penetration is usually not a problem.

Soils of the latosol type that are found in the warmer climates show little distinct horizon development. They are high in free iron and aluminum oxides, and the clays are mostly of the 1:1 lattice type. In spite of very low organic matter content these soils are usually well aggregated, or at least have good physical properties. It is the iron and aluminum oxides, and other inorganic substances, in these soils that are the important aggregating agents, and not organic matter.

Mention should also be made of desert soils since they are agriculturally valuable where irrigation is feasible. These unleached soils show little profile development, are usually low in clay content and have good physical properties. The amounts of organic matter in the B-horizons of desert soils are very low but calcium, magnesium and potassium are fairly abundant. Nitrogen, phosphorus and sulfur are likely to be deficient. When irrigated and heavily cropped, the need for fertilizers is likely to become evident at an early date. Desert subsoils are, however, not likely to present unusual plant growth problems provided the alkali content is not too high and the land lends itself to good water management. This is also usually true of semiarid soils.

Nutrients

Soils of the B-horizon vary widely in nutrient content but are commonly higher in total mineral nutrients, other than nitrogen, than are surface soils. The content of available nutrients may be lower but this is dependent very much on the soil type and how it has been treated. Under conditions of heavy fertilization and cropping, organic matter tends to increase in both the A- and B-horizons, but chiefly in the upper 6–10 inches, and much of the available nutrient supply is locked up in this organic matter. Some of the fertilizer nutrients added to the topsoil do leach into the subsoil but this is generally a slow process. An exception is nitrate nitrogen, but this is a transient element that remains in the subsoil only so long as downward water movement is insufficient to move it to lower levels, or until it is assimilated by the crop or microorganisms.

Soil reaction and toxicity

Under intensive cropping systems humid subsoils tend to become acid, because the nitric acid formed in the topsoil combines with basic elements as it moves downward through the A- and B-horizons. The bases removed from the topsoil can be replaced readily by additions of fertilizers and lime but these basic elements move downward largely as neutral salts; lime moves very slowly (see Chapter 23). A pH in the range of about 3.5–4 is a very critical one for the growth of most plant roots. The growth of many legume roots, and likewise nodulation and nitrogen fixation, are likely to be prevented or greatly curtailed at values considerably above this range. The addition of basic materials to the subsoil by means of deep plowing operations is one method of raising the pH of subsoils, but this is not likely to be a practical and widely-adopted economic solution to the problem. Where the subsoil is exposed, it can be limed and treated as are A-horizon soils.

In acid subsoils a toxic condition sometimes develops that may be due to either aluminum or manganese, or occasionally to other minor elements. This is seldom a serious agricultural problem. Likewise, as pointed out in Chapter 18, toxic organic substances may occasionally be encountered. Poor aeration in subsoils may also be responsible for the production of toxic reduced compounds.

Toxicity of subsoils resulting from the presence of alkali salts is commonly observed in irrigated regions where the rainfall is inadequate to remove the salts that have accumulated. If sodium salts are present in abundance the inhibition of plant growth is often due in part to the poor physical conditions as well as to the salt concentration.

Root proliferation

The conditions in subsoils for root growth are usually less favorable than in the topsoil. Limited extension of the root system, as already stated, is likely to be encountered in subsoils that are very high in clay content, poorly aggregated, or inadequately aerated. In addition, where pan layers exist, root growth may be greatly inhibited or entirely prevented. Most of these conditions could be alleviated if organic matter could be introduced but this is not feasible except where the subsoil is exposed.

The possibility that limited root development is attributable to insufficient available major and minor nutrients has received considerable attention. Sometimes the addition of available nitrogen and phosphorus has increased the depth and extension of root systems, but in most cases the increase has not been marked, and there was no certainty as to how much of the increases obtained was due to the nutrients per se, and how much to the mechanical operations involved in the addition of the nutrients. Where the A-horizon is present, most of the nutrients needed for growth in the subsoil are readily obtained from the topsoil, but in exposed subsoils added available nitrogen and phosphorus may be very essential for extensive root proliferation. If the physical conditions are satisfactory, plants produce a surprisingly large amount of roots on a minimum of nutrients; they appear to send out roots in search of nutrients, particularly nitrogen.

A striking illustration of the effect of organic matter on root growth is occasionally observed in heavy, poorly-aggregated, clay soils where organic matter has been buried in a limited area, rather than being mixed with the entire soil mass. If a fork full of manure, for example, is buried at a depth of one or two feet in such a soil, and a plant root reaches it, a mass of very finely-divided roots is likely to form throughout the manure. The adjoining clay may be almost entirely devoid of roots. Obviously a large number of factors are responsible for such an extensive proliferation of roots.

Pan layers

Winters and Simonson (1951) classify pans as claypans, fragipans, and hardpans. The three types are respectively defined as layers of clay accumulation, compact horizons without definite cementation, and horizons with cementation. The distribution of these pans and their mode of formation is considered in some detail by these workers.

The claypans in different types of B-horizons have clay contents in the range of 25–60%, consisting mostly of montmorillonite and illite. The density and low porosity of these subsoils result in slow movement of water through them, and restricted root development due in part to poor aeration. The fertility status of the claypans is usually fairly good although some may be acid. When these subsoils are exposed, the high degree of plasticity and low organic matter content make problem soils of them, and tillage is very difficult.

Fragipans commonly occur at depths of 1–2 ft. or lower and exist either as faint pans or distinct ones that are very hard when dry, and friable when wet. The fragipans are usually of medium texture and high in silt but in some cases may contain considerable clay or sand. They have high density and extremely low permeabilities, and it is these physical factors rather than low fertility that are responsible for the absence of appreciable root development in most of them. When exposed, fragipans usually become very hard but gradually slake down and more or less completely disintegrate.

Hardpans are cemented layers that remain intact when either wet or dry. The usual cement consists of either iron oxide, calcium carbonate, silica or organic matter, singly or in combinations. Winters and Simonson (1951) list and describe the main types of hardpans as ortsteins, laterite crusts, iron-silica hardpans of dry regions, and caliche. The fertility of these hardpans is usually low, but this is of comparatively minor importance in plant culture; the dominant feature is that they are largely impervious to root development. When exposed and broken up they make a poor growth medium even if adequate nutrients are applied. The broken-up hardpans may also slowly become recemented. This occurs commonly when the subsoil including the pan layer is subjected to deep plowing or subsoiling. Because of the rock-like characteristics of hardpans, and the nature of the cementing materials, the addition of organic matter, if possible, is not likely to overcome these physical handicaps to root growth.

CONTRIBUTION OF UNDISTURBED SUBSOILS TO PLANT GROWTH

Much emphasis has been placed on the plowed layer and its contribution to crop production, and comparatively little research has been done on the subsoil. In fact, in general discussions of the depletion of soil fertility the subsoil is often ignored, even though we know that it is often higher in essential nutrients, other than nitrogen, than is the A-horizon. These mineral nutrients may be less available to plants than those in the surface layer that is constantly subject to weathering and oxidation, but nevertheless subsoils do contribute in a major way to plant feeding. The plowed layer is only 6–12 inches deep whereas the subsoil tapped by the root system may have a depth of several feet.

A few years ago there was considerable discussion of the effects of sheet erosion that gradually removes much of the A-horizon. Some scientists concluded that the removal of the topsoil might not be objectionable, because this would merely allow the farming of more of the subsoil that was better supplied with mineral nutrients than was the topsoil. Such a conclusion is obviously extreme, especially now when nutrients can be purchased comparatively cheaply. The replacement of a topsoil, lost by erosion, is a slow and expensive process and there is no doubt as to its overall value in comparison with subsoils. This is strikingly true in most humid regions. The poorer the physical condition of the subsoil, and the lower the content of organic matter, the greater is the difference in value. Furthermore, many of our soils are shallow and bedrock may be only 2 or 3 ft. or less below the surface. It is obvious that appreciable erosion of such a soil would soon remove it from general cropping and leave it suitable only for tree crops or general reforestation.

Often insufficient emphasis is placed on the importance of the subsoil as the chief reservoir of moisture upon which the crop must depend. This importance is brought out strikingly if an attempt is made to grow a crop on a soil that has a hardpan that stops root growth at plowsole depth. Enough has already been said in previous chapters to emphasize that often much more of the crop's water supply is obtained from the subsoil than from the topsoil, and the amount of water derived from the subsoil increases as the roots increase in length and undergo extensive branching.

EXPOSED SUBSOILS AS PLANT GROWTH MEDIA

Considerable experimental work has been reported in recent years dealing with crop production on exposed subsoils. In some of the more interesting experiments the topsoil has been removed to various depths, and the remaining soil subjected to different farming and fertilization practices in an attempt to make this exposed subsoil as productive as the original undisturbed horizon. In such cases where the B-, C-, and D-horizons are left undisturbed, the chances of success are usually greater than when working with subsoils removed mechanically during construction operations. A few representative experiments are reported below.

Studies with two Ohio soils were reported by Bachtell et al. (1956) using different cropping systems and fertilizer treatments. One soil (Canfield silt loam) was a virgin one, whereas the other (Celina silt loam) had been cropped for many years and was low in fertility. Comparisons were made between undisturbed soils and those from which the topsoil was removed. Crop production on the Canfield subsoil was improved by the best treatments, but the building of topsoil from the subsoil was far from complete at the end of two decades. Bulk density was changed very little and soil aggregation remained markedly inferior in the subsoil as compared with topsoil. The growing of green manures for plowing under gave less satisfactory results than the use of alfalfa-grass meadows. The Celina soil made even a poorer response to treatments than did the Canfield soil, apparently because of low fertility and high clay content. Undoubtedly if much larger applications of nitrogen and phosphorus had been made to these exposed subsoils throughout the experimental period, the crop yields would have been nearer those obtained from the undisturbed soil, but this would probably not have greatly improved the unfavorable physical conditions.

Smith et al. (1967) reported results with an Austin clay from Texas that agree rather closely with those reported by Bachtell et al. for Ohio soils. Thirty-one years after 15 inches of soil was removed from the Austin clay, fertilized grain sorghum in a favorable season produced only slightly less than on normal soil; in less favorable seasons the yields were several hundred pounds per acre less on the desurfaced soil. They state that these low yields during unfavorable seasons probably resulted from "intensified drought and heat damage related to higher bulk density and lower porosity of the top 18 inches of soil. This physical characteristic changed only slowly, if at all, during 31 years after desurfacing." Erosion was greater on the desurfaced plots, as would be expected, because of low porosity and low organic content that result in decreased infiltration. The failure to build up a normal topsoil after 31 years emphasizes the value of the normal virgin topsoil.

Eck et al. (1965), working with a Pullman silty clay loam, observed that nitrogen was necessary for maximum yields of grain sorghum on both undisturbed soil and on exposed subsoils. Nitrogen and phosphorus additions restored yields where up to 12 inches of topsoil was removed; on 16-inch cuts the yields were 80% of those on similarly fertilized, undisturbed soils. Other studies with this soil (Eck, 1968, 1969), similarly emphasized the necessity for adding nitrogen and phosphorus when farming a soil from which the surface has been removed. Water-storage capacity is also less in such a soil and this can affect yields when moisture is limiting.

From greenhouse studies with three soils from the Southern Great Plains, Eck and Ford (1962) concluded that these soils are amenable to land-forming practices that involve removal of topsoil. It is only necessary to add nitrogen and phosphorus as needed. The authors point out, however, that these three soils were deep and permeable and had good tilth; in other soils of high clay content in the subsoil the removal of the topsoil would be expected to present major physical problems.

In studies with a Gardena fine sandy loam that had been subjected to land leveling, Carlson et al. (1961) found that it was necessary to apply N, P, Zn and manure to make corn yields on the subsoil equal those on the surface soil.

Results similar to those of Eck and Ford (1962) were reported by Reuss and Campbell (1961), working with Montana subsoils that had good physical properties. These soils required both nitrogen and phosphorus, and gave an additional response if heavy applications of manure were also applied.

Experiments conducted in Iowa on a Marshall silt loam by Engelstad and Shrader (1961) and Engelstad et al. (1961), indicated that equal corn yields can be obtained on permeable surface and B-horizons if adequate nitrogen fertilizer is applied (Table 26.I).

TABLE 26.I

YIELDS OF CORN GROWN ON SUBSOIL AND NORMAL SURFACE SOIL AS AFFECTED BY ADDITIONS OF NITROGEN* (from ENGELSTAD and SHRADER, 1961)

1958			*1959*		
nitrogen treatment (lb./acre)	*corn yield (bu./acre)*		*nitrogen treatment (lb./acre)*	*corn yield (bu./acre)*	
	subsoil	*normal soil*		*subsoil*	*normal soil*
0	31.4	77.3	0	30.3	82.0
67	83.5	100.5	60	69.6	105.4
133	101.3	103.5	120	106.6	122.3
200	107.3	104.8	180	122.4	122.6
267	105.1	96.1	240	122.8	116.7

*All plots received adequate phosphorus and potash.

Yields of subsoil control plots that received no nitrogen were 45–50 bushels per acre lower than from surface soil plots. The production of maximum corn yields on subsoil required 35–52 more lb. of nitrogen per acre in 1959 than on normal soil.

The experiments quoted here, as well as many others, would seem to indicate that in most cases the farming of subsoils that are deep and permeable is likely to give good results if nitrogen, phosphorus, and sometimes minor elements, are supplied. This seems to be true of most of our semiarid soils where leaching has never served to stratify the soils. Land leveling in this area is generally feasible, whereas it would be very destructive if applied to most soils in the humid area. Fortunately, there is little need for this operation where irrigation is not practiced.

In Chapter 7, reference is made to the rather unexpectedly high levels of organic matter that are found in many soils of Puerto Rico. Smith et al. (1951) rightly attributed this in large part to the lack of killing frosts; if vegetation remains alive it does not decay. Under these tropical conditions, Smith et al. point out that there can also be a rapid buildup of organic matter in exposed subsoils if adequate nitrogen is supplied through legumes or manures. They state that "tropical kudzu with grass can add more than 300 lb. of nitrogen to the soil per acre yearly. The greatest early build-up is in the surface 3 inches of soil. Mulching with trash low in nitrogen and grass culture under treatment with nitrogen-rich manure have also been shown to increase quickly the soil organic matter and nitrogen levels of exposed subsoil. Thus it is clear that, although the most practical and economical approach may be to preserve present organic matter and nitrogen levels wherever possible, it is still feasible to reclaim and build up the organic matter and nitrogen in Puerto Rico soils where it has been removed or destroyed."

RECLAMATION OF MINE SPOILS

Mine spoil consists of soil or soil material, and rock and other materials that are removed in mining operations from above coal or other mineral deposits. This overburden may be either deposited back into the area from which the mineral has been removed, or be left on undisturbed land alongside of the cut. The mining operations are conducted by means of draglines, shovels and various types of heavy equipment designed specifically for rapid removal of the overburden. The bulldozer is used chiefly for backfilling or grading of the spoil after removal of the coal or other mineral.

According to Whitt (1968), more than 3 million acres of land in the United States have been subjected to surface mining, and about two-thirds of this has left problems of soil erosion, sedimentation, and water pollution. Most of the affected land is privately owned and can be reclaimed and returned to productive use.

Land that has recently been strip-mined for coal presents an ugly and desolate appearance. The overburden is commonly left in steep and jagged ridges that, when abandoned, are often slow to become covered with vegetation. Any cliffs and undisturbed rock upon which the coal was deposited may remain largely without vegetation for years unless some of the overburden is used to cover these areas.

The after effects of strip-mine operations where no effort was made to restore the land and environment can be very depressing and discouraging. Drapkin's (1970) vivid description of such an area follows: "The streams around this crossroads hamlet (Lost Creek, W. Va.) run yellow-red with the acid drainage from mines. Huge bare strip-mine excavations slash across miles of once-green mountains. Vacant mine buildings rot and sag. Rusting, abandoned mining machinery clogs rutted back roads . . . . .Such scenes are to be found in the countryside surrounding hundreds of semi-rural communities scattered across Pennsylvania, West Virginia, southern Ohio and eastern Kentucky." He describes the area in West Virginia as "dead beyond all reasonable hope of reclamation". This pessimistic statement may represent an over-reaction to an admittedly depressing and messed-up landscape and ecology.

Drapkin states further that "federal pollution-fighters estimate that merely to clean up stream-polluting acid mine drainage might cost up to $10 billion. The costs of filling in old mines, smothering underground fires and removing the mountains of coal waste haven't even been guessed at." Some observers doubt that the job can be done at any price. Many of the streams are so polluted that they are bereft of normal aquatic life.

In recent years there has been an increasingly strong demand that these stripped areas be reclaimed, and considerable legislation has been passed to require that this be done. Reclamation does not ordinarily mean that the mined areas must be restored to their original appearance and use. This is often impossible, uneconomic, and even undesirable. The primary aim is to restore the natural beauty of the landscape, eliminate stream contamination, and make the stripped area serve some good purpose in the economy. Such a good purpose may occasionally mean the use of the land for the growth of cultivated crops but much more often it will be used for grazing, reforestation, recreation and fish and wildlife. Some of the deeper cuts may be made to serve as small lakes and in this manner become even more valuable to the public than if used for grazing or forests. Most strip-mine areas lie in regions of low acre evaluation which means that extensive reclamation is not profitable to the landowner. The expense must be borne largely by the mine operator or by the state or federal government.

The present discussion will deal chiefly with the characteristics of the spoil material and some of the chief problems encountered in the process of establishment of a vegetative cover. For those who are interested in the broader aspects of strip mining, and the utilization of the strip-mine areas for various purposes, reference should be made to the following recent publications: Kohnke (1950); Limstrom and Deitschman (1951); Grandt and Lang (1958); Limstrom (1960); Sawyer (1962); Roseberry and Klimstra (1964); Jemison (1965); Montgomery (1965); Schessler and Droege (1965); Van Landingham (1965); Udall (1966); Chapman (1967); Plass and Burton (1967); Striffler (1967); Vogel and Berg (1968); and Whitt (1968).

Topography

In coal-mine operations it is customary to make a long cut across the slope and deposit the overburden on the lower side. The cut may be of any depth up to about 100 ft. This operation leaves a steep undisturbed cliff-like bank on the upper side and a flatter spoil bank on the down side. If the original slope of the land was not steep, several parallel cuts may be made leaving a series of spoil banks 30–80 ft. apart and initially having slopes of perhaps 50–90%. These ridges are usually of fairly uniform height but may be very irregular if the overburden has been removed by means of a dragline. In steep, rugged country it may be feasible to make only one or two such cuts because of the amount of overburden that would have to be removed.

During the first two or three years some settling occurs and the slopes of the spoil banks decrease considerably, especially where the ratio of soil material to rocks is high. Erosion is also severe initially unless a high percentage of the overburden consists of rocks. Most of the sand, silt and clay on the outside of the spoil bank is rapidly carried by water to the valleys, and some of the finer particles may reach the streams.

Nature of spoil bank material

Physical composition

Spoil bank material is very variable in physical composition but rocks of various sizes usually predominate over soil material of less than 2 mm diameter. The kind and amount of rocks in any given portion of a spoil bank are very variable and dependent upon the geology of the region and on the method of mining. Sometimes much of the soil material may be deposited at the bottom of the bank and the larger rocks placed on top. In other cases the reverse procedure may be followed, or perhaps no uniform system is used. If shales, sandstones and limestone are abundant, as is often the case, they are likely to be shattered to a considerable extent during mining operations, and the breakdown is further accelerated as these undergo weathering on the top and sides of the filled ridges. In glaciated areas a considerable portion of the overburden may consist of heterogenous soil material, or perhaps of layers of sand, silt and clay. As this is removed during the mining operation it may be deposited in local parts of the bank or in mixture with the rocks. Obviously, the spoil bank initially has no differentiation into horizons, and no profile in the sense that the term is applied to soils. Organic matter is also present only in minimum amounts. As weathering proceeds, the softer rocks in the upper one-foot layer slowly disintegrate. A small amount of organic matter accumulates at the surface, the amount depending upon the extent to which plants are able to live in this environment.

Chemical composition

Since the physical make-up of spoil banks varies so widely, it is obvious that the nutrient content also varies similarly. The amount of potentially available potash is likely to be as great as or greater than on nearby undisturbed soils, but the availability may be low. The same is true of phosphorus, but the content of this element is more variable. Since organic matter in new spoils is extremely low, the nitrogen content is also very deficient. It increases as the spoil banks become covered with vegetation, but only very slowly unless much of the plant cover is leguminous. Minor elements are usually present in adequate amounts for plant growth. The availability of all of the nutrients is much dependent upon the pH of the material.

The reaction of spoil material commonly varies from slightly alkaline, usually where limestone is present, to highly acid. Usually the range is between pH 4 and 6, where most plants can grow satisfactorily, but may be as low as pH 1. The biggest problem is encountered in spoils containing so much pyrite that the soil material is made highly acid. Iron sulfide is a common constituent in the strata surrounding seams of coal. It is only when it is exposed to the air, and undergoes oxidation to form sulfuric acid, that it becomes a serious hindrance to the revegetation of the exposed materials. This acidity may be neutralized if limestone is abundant in the immediate vicinity. Sometimes the oxidation process can be slowed down by covering pyrite-containing material with spoil that is free of it. Where pyrite is present in limited amounts, its oxidation may be allowed to proceed normally until most of the exposed material has been oxidized. This is a comparatively slow process. Neutralization of the sulfuric acid by outside additions of lime is usually not a feasible operation unless the pyrite area is limited.

The sulfuric acid formed by oxidation of sulfides may react with iron, manganese, and aluminum that are naturally present in most spoils. These comparatively soluble sulfates are readily assimilated by plants, and marked toxicity or death may result. This type of toxicity is often more harmful than acidity as such.

Water relations

Infiltration into fresh spoils is likely to be limited because of the steep slopes, lack of organic matter, and poor aggregation of the soil material that is at the surface. In fact, any such soil material there initially is subject to rapid erosion as the water rushes down the steep slopes. The presence of areas of clay that has been compacted during or after the mining operations also decreases infiltration. Compacted clay acts like a claypan, since it is not aggregated and permits only slow downward movement of water. If the clay is trapped on the surface by rocky material, it is also subject to raindrop splash and sealing or crusting that impedes water entrance and movement. The presence of a high percentage of rock at the surface may act like a mulch and favor increased infiltration. In fact, some graded spoils, not too high in clay, show more rapid infiltration than do normal soils.

The mixture of rocks of various sizes in a spoil bank insures that the mass of the overburden has a loose structure with many large pores. During the mining operation the overburden is increased about 30–50% over its original volume. Any moisture that gets into the mass is therefore likely to be held longer than would be the case in a normal soil profile. This water retention is the result both of broken capillarity and absence of transpiration in a fresh spoil. Even though infiltration is often low, the spoil bank may accumulate considerable moisture during the rainy seasons, and hold it rather tenaciously. In summer months the surface on spoil banks exposed to the sun and wind may become very dry, but as some vegetation becomes established crusting is reduced and infiltration is increased.

Establishment of a vegetative cover

The first step in the reclamation of a coal mine spoil is to make a quick physical and chemical study and evaluation of the spoil material to determine its possible uses. The chemical studies should include quick tests for acidity, sulfide and carbonate (Kohnke, 1950). The physical evaluation includes the determination of kind and amount of rock, texture of the soil material, slope of the spoil bank, drainage, and the location of the bank with relation to surrounding activities. Since any spoil bank consists of a heterogenous mixture of rocks and soil materials, not uniformly mixed, it is necessary to sample the bank at numerous locations in order to get a true picture of its capabilities.

The second step in reclamation is to decide what can best be done with the spoil bank, considering its capabilities, location, climate, costs of reclamation, and probable economic value after reclamation. The chief potential agricultural uses of mine spoils include the growing of field and fruit crops, pastures, and forests. In addition, certain areas may be utilized for fish and wildlife, general recreation, and as building sites.

Grading

Where no grading of spoils is to be done, the growing of general farm and horticultural crops is excluded, and the establishment of vegetative cover is limited largely or wholly to forests. Even pastures are difficult to establish and graze because liming and fertilization are not possible, and the steep slopes preclude satisfactory grazing. For pastures, legumes are required to furnish nitrogen, and most spoil banks are more acid than pH 6 to 6.5, where legumes thrive. Of course where the spoil bank contains considerable limestone, and is not too rocky, some legumes and grasses may be established readily. If the pH of the spoil is below about 4.0, even trees are not likely to grow until oxidation and leaching have removed most of the free acids.

Grading greatly widens the land use capabilities by decreasing the slopes and permitting the use of various kinds of farm machinery. Land that was suitable only for forestry and wildlife may, after grading, become suitable for permanent pasture, fruit crops and even cultivated crops. The whole process of establishment of a near-normal soil is speeded up when the soil slope is markedly decreased, erosion retarded, and the normal farming operations of liming, fertilization, seeding and cultivation made possible. Crops such as legumes and grasses, if they can be grown, are more effective than trees in hastening the formation of a soil with good structure and organic matter. A by-product of grading operations is a marked improvement in appearance of the landscape, which is important along highways and near centers of population.

Grading operations must be planned in advance to fit the nature and lay of the spoil banks, and the use to be made of them (Schessler and Droege, 1965). If only forests are wanted then no grading may be necessary except possibly for provision of roads and proper drainage. If it be assumed that pastures, fruit trees, or cultivated crops are to be grown eventually, if not immediately, then careful attention should be given to the length and steepness of the slopes to be established. Kohnke (1950) states that "pasture land should have no slope steeper than 25 percent in order to permit safe operation of agricultural equipment, while for cropland and orchard land the maximum slopes should be 10 percent in order to avoid serious erosion hazards". Short slopes are essential if erosion is to be minimized, except where the spoil material is very porous.

How much grading is necessary or desirable? This question has been much discussed and the general conclusion seems to be that grading should be held to a minimum, which in turn depends upon the characteristics of the spoil material, lay of the land, use to be made of the spoil, and the economics of the operation. It is also agreed that the ideal time for grading is while the mining operation is in progress or as soon thereafter as possible. If grading is delayed until the spoil material is saturated with water, compaction may markedly inhibit root growth and also increase erosion as a natural consequence of reduced infiltration. As the clay content increases above 15%, compaction becomes an increasingly serious problem. Recommendations that apply to spoils located in hilly, rocky regions, where there is only a thin coating of soil, are not likely to apply very closely to spoils located in a glaciated region where clay, silt, and sand abound, and of course the reverse is true. This difference in the character of the overburden is very important in planning the grading and use of the spoil.

If only trees are to be grown, it is usually satisfactory to practice strike-off grading which involves two or three bulldozer passes over the ridge of a bank when moisture conditions are favorable, leaving a flat top 15–20 ft. wide. This minimum-type grading produces only a limited amount of compaction, yet facilitates access and planting.

Where the last mining cut has been made, exposing bare rock at the bottom and a cliff-like rocky bank, the cut may in some cases be partly covered with soil material, but often a better practice is to use the cut as a pond for livestock, wildlife or recreation. This is not advisable if the water is too acid to support plant and fish life, or disappears during the summer months.

In some European countries extreme care is exercised to assure that the land is restored to its original, or better, condition. In open-cast (strip) mining in Great Britain, for example, Striffler (1967) states that the soil and subsoil are stripped and piled separately. The general practice is to remove about 12 inches of soil and 24 inches of subsoil. Using dragline excavation methods, the spoil material is hauled to separate piles and returned after the coal has been removed. After grading to a maximum slope of 33% and terracing, if necessary, the subsoil and topsoil are returned. The land is now ready for immediate seeding to grasses, small grains and legumes; where the terrain is very rugged it may be planted to evergreen trees. This expensive system of mining and reclamation assures that the land can be utilized as desired without the usual problems encountered in farming rocky overburden with no topsoil covering.

Semotán (1962), in his discussion of the reclamation of the spoils from brown-coal strip-mines of Czechoslovakia, emphasized the importance of using the right technology of strip mining, including the selection of soil materials that will, when placed on the top of the spoil, serve as satisfactory subsoil and topsoil ingredients. The next step is to get humus into these soil materials. Since the addition of crop residues is a very slow method of building up humus, he recommended the addition of farm manures, fertilizers, moor-soils and suitable oxyhumolithes or organogenous soils found in the vicinity of brown coal deposits. Not all soil materials are suitable for conversion into good agricultural soils.

Establishment of forests

Although trees commonly grow well on ungraded spoils, some grading may be advisable. Usually the trees must be planted individually since direct seeding has seldom proved satisfactory. Any areas that are not more acid than pH 4.0 are suitable for planting. The appearance of volunteer vegetation is a good indication that the more acid spoils will now support trees. They are likely to respond to nitrogen fertilization, but this practice is seldom followed.

New spoil banks are unstable and may settle as much as three feet during the first year. The settling process then slows down markedly but continues at a slow rate for several years. Where the spoil has been deposited on top of undisturbed soil on steep banks, slides often occur. Planting should not be done until the spoil has completed most of its settling, otherwise the roots may be injured and left partly exposed.

Schessler and Droege (1965) state that studies have revealed that the amount of soil particles (2 mm or less) in spoil banks commonly comprises 17–57% of the overburden. As little as 20% soil material has been shown to support planted trees. It is this finer material that determines the water-holding capacity of the spoil and the probability that trees or other plants can become established.

The most commonly used species of trees are pines and black locust (Youker, 1964) but most of the common hardwoods and softwoods have been used with fair success (Limstrom and Deitschman, 1951; Limstrom, 1960; Chapman, 1967). Results reported by Chapman show that ungraded spoils are a more satisfactory growth medium than are graded ones. More information on this subject is much needed. Success in the establishment of forests is dependent upon the spoil characteristics, amount of grading, the tree species, and various climatic factors. Deficient nitrogen is undoubtedly a major limitation to tree growth on fresh spoils unless the spoil happens to have considerable topsoil or glacial till incorporated in it near the surface.

Vogel and Berg (1968) recommend that in order to minimize runoff and erosion while trees are becoming established, herbaceous vegetation should be used to provide quick cover. They suggest weeping lovegrass (*Eragrostis curvula*), Blackwell switchgrass *(Panicum virgatum)*, and K-31 tall fescue *(Festuca arundinacea)*. These grasses alone make little growth on most spoils unless nitrogen fertilizer is added. The more acid tolerant legumes suitable for spoils, mentioned by these workers, include birdsfoot trefoil *(Lotus corniculatus)*, sericea lespedeza *(Lespedeza cuneata)*, Kobe lespedeza *(L. striata)* and Korean lespedeza *(L. stipulacea)*. At pH values above 5 these legumes will nodulate and fix nitrogen. Since the addition of fertilizers to spoils is usually not feasible, it is common practice to seed mixtures of legumes and grasses, or perhaps legumes initially and then grasses later, if desired.

Establishment of pastures

Pastures may be established on both graded and ungraded spoils, but are not likely to be very satisfactory unless some leveling of the material is brought about. Aside from grazing difficulties, the likelihood of getting heavy vegetation on nitrogen-deficient, steep banks is not very good. Of course leveling does increase soil compaction and all its accompanying problems, but the compensating factors are large. Where the surface is not too stony, farm equipment can be used and liming, fertilization and seeding are greatly facilitated. The seeding of mixtures of legumes and grasses that are known to be adapted to the region will start the revegetation process, but it is likely to be three or more years before plant coverage of the soil is satisfactory for extensive grazing (Grandt and Lang, 1958).

The conversion of spoils into grazing land is not likely to be a profitable adventure for the farmer unless a portion of the cost is borne by the mining company or by state or federal government. In either case the reclaimed mined area should be incorporated, if possible, with a nearby farming operation located on undisturbed soil.

Growing farm crops and orchards

The use of spoils for the growing of rotation crops or fruit trees necessitates that the area be graded to a slope not greater than about 10%, unless erosion is to be controlled by the use of hay crops, terraces, and minimum tillage methods. It is also essential that few resistant rocks be present in the surface one foot. Since the presence of any appreciable amount of non-disintegrating surface rocks eliminates the spoil bank as a medium for the growth of cultivated crops, it is obvious that few spoil banks can be utilized for this purpose.

On the graded spoil banks that are suitable for general farm crops, or are capable of being made suitable, the common practice is to seed the slopes to legumes and grasses that may be used for hay or pasture (Grandt and Lang, 1958). After several years, depending upon the physical and chemical properties of the spoil material, the area can be utilized for general cropping. Fruit crops may be grown sooner than cultivated crops if the acidity is not prohibitive.

Wilson (1957) found that on spoils, as on normal soils, the type of vegetation was an important factor in aggregation. On coal-land spoils aggregation after 10 years increased in the following order: nonvegetated < pine < locust < forage grasses and legumes. The reasons for the effectiveness of finely-divided roots of grasses and legumes are discussed in Chapter 16. Wilson states, further, that century-old iron-ore spoils, covered with trees and shrubs, were not as well aggregated as the adjacent unstripped soil.

The new soil profile

There is essentially no information on the appearance of a mine spoil profile after 50 or more years. We know that initially the physical disintegration of the shale and sandstone at the surface takes place rapidly; chemical decomposition takes place less rapidly.

Limestone disappears slowly. As a result of these weathering processes a surprisingly large amount of soil particles less than 2 mm in diameter can form. In 5–10 years the spoil surface may resemble undisturbed soils provided few non-disintegrating rocks are present. The weathering process is for the most part limited to the first foot or so where freezing and thawing occur, and where chemical and biological processes are active.

Plant growth also accelerates the formation of the new topsoil. Any root growth into deeper spoil material would tend to improve structure and aggregation of the clay that often inhibits root growth initially. Gradually a build-up of organic matter in the region touched by the roots would also hasten the formation of a true soil profile. Resistant rocks would be expected to remain, and the roots would have to grow around them. Probably the chief change that would occur in the deeper layers of the spoil would be the gradual settling, and filling up of the pores with clay and silt. As this occurs, capillarity would doubtless be restored gradually but high clay content would make a very impervious subsoil. Certainly the amount of topsoil, glacial till, clay and kind of rocks originally placed in the spoil bank would affect the characteristics of the new soil profile. It is obvious that the soil profile, except for the first two or three feet, would never resemble a natural soil profile where there is commonly a distinct separation of disintegrated material (soil and subsoil) from the parent material.

REFERENCES

Bachtell, M.A., Williard, C.J. and Taylor, G.S., 1956. *Ohio Agric. Exper. Stn., Res. Bull.*, 782: 1–35.

Carlson, C.W., Grunes, D.L., Alessi, J. and Reichman, G.A., 1961. *Soil Sci. Soc. Am., Proc.*, 25: 44–47.

Chapman, A.G., 1967. *Southern Ill. Univ. School Agric. Publ.*, 29: 1–34.

Drapkin, M.K., 1970. *Wall St. J., April 22*, 175: 1, 17.

Eck, H.V., 1968. *Soil Sci. Soc. Am., Proc.*, 32: 686–691.

Eck, H.V., 1969. *Soil Sci. Soc. Am., Proc.*, 33: 578–581.

Eck, H.V. and Ford, R.H., 1962. *J. Soil Water Conserv.*, 17: 274–275.

Eck, H.V., Hauser, V.L. and Ford, R.H., 1965. *Soil Sci. Soc. Am., Proc.*, 29: 209–213.

Engelstad, O.P. and Shrader, W.D., 1961. *Soil Sci. Soc. Am., Proc.*, 25: 497–499.

Engelstad, O.P., Shrader, W.D. and Dumenil, L.C., 1961. *Soil Sci. Soc. Am., Proc.*, 25: 494–497.

Grandt, A.F. and Lang, A.L., 1958. *Univ. Ill. Agric. Exper. Stn., Bull.*, 628: 1–64.

Jemison, G.M., 1965. *J. Soil Water Conserv.*, 20: 186–188.

Kohnke, H., 1950. *Adv. Agron.*, 2: 317–349.

Limstrom, G.A., 1960. *U. S. Dep. Agric., Handb.*, 166: 1–74.

Limstrom, G.A. and Deitschman, G.H., 1951. *Univ. Ill. Exper. Stn., Bull.*, 547: 201–251.

Montgomery, R., 1965. *Strip Mining in Kentucky.* Ky. Dep. Nat. Res., 56 pp.

Plass, W.T. and Burton, J.D., 1967. *J. Soil Water Conserv.*, 22: 235–238.

Reuss, J.O. and Campbell, R.E., 1961. *Soil Sci. Soc. Am., Proc.*, 25: 302–304.

Roseberry, J.L. and Klimstra, W.D., 1964. *J. Soil Water Conserv.*, 19: 107–110.

Sawyer, L.E., 1962. *J. Soil Water Conserv.*, 17: 65–67.

Schessler, T.E. and Droege, R.F., 1965. *J. Soil Water Conserv.*, 20: 17–90.

Semotán, J., 1962. *Trans. J. Meet. Comm. IV, V, Int. Soc. Soil Sci.*, pp. 871–875.

Smith, R.M., Samuels, G. and Cerunda, C.F., 1951. *Soil Sci.*, 72: 409–428.

Smith, R.M., Henderson, R.C., Cook, E.D., Adams, J.E. and Thompson, D.O., 1967. *Soil Sci.*, 103: 126–130.

Striffler, W.D., 1967. *J. Soil Water Conserv.*, 22: 101–103.

Udall, S.L., 1966. *A Study of Strip and Surface Mining in Appalachia.* U. S. Dep. Interior, 78 pp.
Van Landingham, A.H., 1965. *J. Soil Water Conserv.*, 20: 185–186.
Vogel, W.G. and Berg, W.A., 1968. *J. Soil Water Conserv.*, 23: 89–91.
Whitt, D.M., 1968. *U.S. Dep. Agric. Soil Conserv.*, 33: 123–125.
Wilson, H.A., 1957. *Soil Sci. Soc. Am., Proc.*, 21: 637–640.
Winters, E. and Simonson, R.W., 1951. *Adv. Agron.*, 3: 1–92.
Youker, R.E., 1964. *J. Soil Water Conserv.*, 19: 146.

Chapter 27

ORGANIC MATTER AND SOIL CONSERVATION

INTRODUCTION

There is probably no natural asset that is of greater importance to man than a fertile soil. This is well expressed by Langenkamp (1965) in the following words: "Human vanity, it has been said, can best be served by a reminder that, whatever his accomplishments, his sophistication, his artistic pretensions, man owes his very existence to a six-inch layer of topsoil – and the fact that it rains." It is the upper layer, where most of the organic matter with its high content of available nutrients is concentrated, that is of most immediate value in crop production. This valuable topsoil was built up very slowly by natural processes over periods of thousands of years. Over much of the inhabited portion of the earth during the period of at least 7,000 years since man began cultivation, much of this natural gift of nature has been removed from its place of origin, and the soil often made almost valueless for crop production. The material that nature built up very slowly has often been destroyed very rapidly, and over the centuries the rate of destruction in many areas has increased as population density and food demands have increased. The destruction has been especially severe in many parts of China, the Near East, North Africa and other Mediterranean countries. The desolate landscape and the sad state of agriculture in many sections in this broad area have been vividly portrayed by Bennett (1939), Lowdermilk (1953), Stallings (1957) and many others.

When the first settlers arrived in what is now the United States, and cleared away the forests and put the land under cultivation, they were soon confronted with severe soil erosion at most of their locations. Soils on the East Coast were for the most part shallow and sloping. The settlers soon observed that largely as a result of soil erosion, the productivity of these cleared areas decreased rapidly and substantially. But at that time virgin land was abundant and all that was necessary was to clear new areas and abandon those that were "worn out". Little or no attention was given to means of preventing erosion and maintaining fertility. In fact, little was known about erosion control, and of course fertilizers, as we know them today, were nonexistent. Moving to new areas did involve much labor in the clearing process, but there seemed at that time no practical alternate choices.

Even before the end of the eighteenth century much of the areas on the East Coast that had at one time been cropped were now abandoned to forests. Lands farther west that were far more fertile took the place of the abandoned eastern acres. But the settlers soon found that even many of these fertile areas did not long continue to produce as they did initially. This was due in part to removal of nutrients, but also to a great extent to erosion that carried away the topsoil with its valuable organic matter. Even in the early part of the twentieth century, the writer knows from personal observation that it was common practice in Kentucky to clear a new area each year or so for tobacco production. This crop was considered as such a heavy feeder that new land was deemed essential for its satisfactory culture.

Eventually, however, there was little virgin land left and the farmers had to depend on the land that they already had. On the more hilly sections, yields often decreased to the point that profitable crop production by the old methods was no longer possible. Thousands of acres in many states were abandoned in the Midwest just as had occurred earlier on the Atlantic Coast. The percentage of abandonment in the Midwestern states was less, largely because the land was less hilly, and the soils deeper and naturally higher in nutrients. West of the Mississippi River, where the rainfall was low, water erosion was less serious but wind erosion became a major problem in some cases as these soils were put under cultivation. Dust storms often produced more damage in this region than did slower-acting water erosion in the humid regions.

Although over the years various writers and scientists called attention to the erosion problem, it was not until the U. S. Congress passed the Soil Conservation Act in 1935 that intensive erosion research was initiated in this country. In the period since that time, extremely marked progress in the solution of the water and wind erosion problems has been made. Farming methods have been so revolutionized since 1935 that there is now no good reason for erosion to be a serious menace in most of our farming operations. This happy conclusion is not the result of the activities of soil conservation alone but is the fruit of intensive research in all phases of agriculture. Soil and crop research has, fortunately, been paralleled by the development of abundant available commercial fertilizers. In fact, many recommended soil conservation practices are dovetailed with recommendation of abundant fertilizers. One operation has so complemented the other that our crop yields are now at an all-time high.

The destructive effects of soil erosion are much in evidence, but the exact mechanisms by which the soil is carried away are much less understood. Heavy rains, running water, and high wind velocities are obviously the causative agents, but when this is stated we have only touched on the more obvious factors or forces. We need to go a little deeper into the phenomena in order to understand better how these destructive forces can be counteracted.

Wind erosion is most obvious, and often most serious, in semiarid or arid regions, where vegetative cover is scarce or absent, but winds can also do much damage in humid regions. Wet soils are not subject to wind transport, but even in humid regions the surface soil can become air-dry in a very short time. The more the soil surface is disturbed by cultivation in the absence of crops, usually the greater is the opportunity for wind to transport it.

WATER EROSION PROCESSES

The removal of soil by water is due to the energy of the falling raindrop, and to the nearly horizontal movement of the water that flows over the soil surface. Both processes or forces act simultaneously. Under conditions that favor erosion, the amount of soil removed increases as the slope increases. A soil of zero slope would obviously not be eroded, although the impact of raindrops would damage the surface of exposed soil by puddling and sealing it against the entrance of water and air.

Losses of soil as a result of water erosion have been shown to be closely correlated with the number and intensity of thunderstorms. This is illustrated by the data from Piedmont soils reported by Barnett et al. (1960), and shown here as Fig. 27.1. They state that during the previous 20 years an average of 11 thunderstorms per year caused 86% of the erosion and accounted for 56% of the rainfall. These storms, lasting an average of about 2.5 h, occur chiefly during the hottest months of the year when evapotranspiration is highest and when little of the rainfall penetrates into the subsoil (see Fig. 13.2 and 13.3).

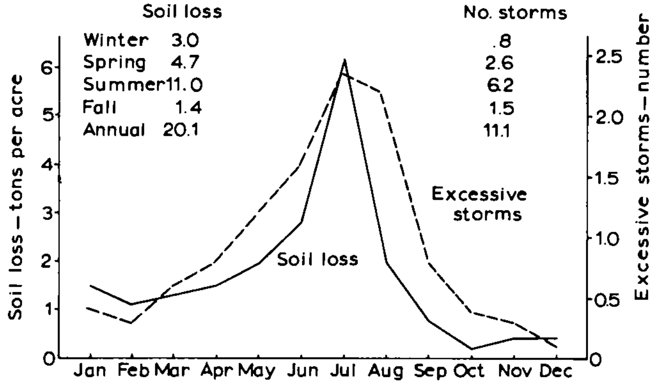

Fig. 27.1. Monthly distribution of soil loss and number of excessive rate storms. (From Barnett et al., 1960.)

As the result of a 5-year field, laboratory and statistical study, Wischmeier and Mannering (1969) concluded that the "properties that contributed significantly to soil-loss variance included percentage of sand, silt, clay, and organic matter; pH, structure and bulk density of plow layer and subsoil; steepness and concavity or convexity of slope; pore space filled by air; residual effects of sod crops; aggregation; parent material; and various interactions of these variables."

Raindrop impact

Kinetic energy, applied to the soil in the form of rain, is a major force in soil erosion, as first shown by Ellison (see Stallings, 1957; and Smith and Wischmeier, 1962). The amount of soil movement is not, however, directly correlated with the amount of force applied, for the obvious reason that so many factors, or forces of a non-kinetic nature, are involved that counteract the applied kinetic energy. Included among these resisting forces are all of the various chemical and physical forces that help to keep a soil well aggregated. By binding many very small particles together into aggregates, the force required to bring about movement is increased many-fold. In this manner clay and silt particles may be made nearly as resistant to transport as are sand particles.

Water erosion starts with the impact of the falling raindrop when it literally crashes into an exposed soil. The force of this blow at any one point is determined by the energy with which the raindrop hits the soil, and the area of the soil that it strikes. The larger the raindrop and the greater its speed, the greater is the impact and the possible damage to a soil. As the intensity of the rainfall increases, the extent of erosion on an unprotected soil also increases. We now know that raindrop splash is generally a bigger factor in erosion than is flowing water.

When a drop of rain strikes a bare soil, or one covered with a thin film of water, it has an explosive effect. The initial compressive effect is followed immediately by a rebound of water carrying fine soil particles. The muddy water falls back to the surface and most of the soil particles are scattered at some distance from the point of initial contact of the raindrop. According to Stallings (1957), on bare soil that is poorly aggregated and highly detachable, more than 100 tons per acre may be splashed by the most beating types of rain. On level surfaces, these soil particles that are being splashed by many hard-driven raindrops, tend to scatter with uniformity over the entire soil surface. On sloping surfaces, considerably more than half of the splashed particles land downhill from the point of impact of the raindrop. The force of rain is, therefore, sufficient to move considerable soil downward on a slope under many conditions, even apart from movement attributable to running water.

Sheet erosion is a term that is sometimes applied to the movement of soil downhill by means other than direct raindrop splash, or in rills and gullies. Raindrops loosen soil particles and transport them to a considerable extent by splash erosion, as already stated. But while this is occurring, a thin film of water is present over the entire soil surface, which is holding fine soil particles in suspension and carrying them along as the water flows slowly downhill. As the volume of water increases and gains momentum, gullies may form, but prior to channelization the water moves as a film or sheet. This sheet erosion is essentially the same, or at least an extension of, splash erosion. Nearly all of the soil particles present in the thin water film are there only because raindrop impacts dislodged them from the soil mass. The greatest amount of this type of erosion occurs on the upper slopes where the full kinetic force of the raindrop is impacted on the bare undisturbed soil; at lower levels much of this energy is used in resplashing soil that had been previously transported from higher levels.

Emphasis above is placed on contact of the raindrop with a bare surface of a fine-textured soil in which the soil particles are readily detached. Rain falling on a very coarse sand would have almost no erosive effect because there would be no muddy water involved, and the rainwater would infiltrate into the soil immediately on contacting it. Likewise, little erosion would occur on a fine-textured soil if it were completely aggregated, and if the aggregates were able to resist the raindrop impact. Soils vary markedly in their ability to "stand up" under raindrop bombardment, but actually no fine-textured soil has aggregates that are so strong that no release of clay particles occurs. The only way to completely prevent raindrop erosion is to cover the soil so that the falling raindrops can never make direct contact with it.

The detachment of soil particles by raindrop impact not only serves to move soil downhill, following the shattering of the clods and aggregates, but leaves the soil surface in a puddled condition. The bombardment and churning of the soil produce a mud that seals the soil surface to such an extent that infiltration is greatly curtailed. The greater the amount of water that is prevented from entering the soil, the greater is the ultimate amount of erosion. As the soil aggregates are disintegrated by raindrop bombardment a small portion of the soil particles, largely the colloidal part, is carried downward in the soil profile for a short distance, and the spaces that were there originally are now filled with these particles, thereby greatly curtailing downward movement of both water and air. On drying, a hard surface crust remains.

Channelized flow

During a heavy rainstorm most of the water that does not infiltrate into the soil flows downhill in channels or gullies that increase in width and depth as the water moves down the slope. Initially this water may have moved over the soil surface in thin sheets near where it fell, but with increase in amount and velocity of water at any one point rills and gullies are formed.

Flowing water moves with much less speed and kinetic energy than do raindrops, but since the amount of force exerted is a function of both volume and velocity, the total force can be very large. So long as the running water is free of suspended soil particles it has comparatively limited eroding powers. The erosive action is increased greatly by soil materials carried along by the running water. They act as abrasives in the turbulent water, loosening soil particles in the channel, and scouring out deeper and deeper gullies. The channel is not carved out uniformly. Irregularities in the soil surface and changes in slope, as well as the varying nature of the soil from place to place, result in turbulence and variations in the speed of flow. Falling raindrops also increase turbulence and release an abundance of soil particles into the moving water both before and after it reaches channels. Obviously the ability of a soil to resist erosion is dependent in a major way on its resistance to particle detachment. As the amount of soil being carried by flowing water is increased, the ability of the water to detach soil particles increases but its transporting power decreases. The net result is likely to be decreased erosion as the soil load nears the limit that the water can transport.

Effect on soil fertility

On cultivated soils located on hilly or rolling landscapes, water erosion can reduce soil fertility and productivity to such an extent during periods of 25 years or less that cultivation is no longer profitable. Such erosion occurred on millions of acres in the East, Southeast, and even in many Midwest and Western soils. In many areas practically none of the original topsoil now remains. It is only the availability in recent years of abundant fertilizers that has made possible the use of many of these severely-eroded soils for general farm crops (see Chapter 26). Other soils that were originally very shallow are now classed as marginal and suitable only for pasture and forests.

The close correlations between depth of topsoil, yield of corn, and percent of organic matter in the top seven inches of soils sampled in Indiana, are shown in Fig.27.2 (Uhland, 1949). Similar data, not shown here, for the same soils sampled to a depth of 20 inches, show an even closer correlation between yield of corn and the amount of organic matter present. In such experiments, where no fertilizer is supplied, the chief factor controlling yields is usually nitrogen, and since soil organic matter has a fairly constant percentage of nitrogen, close correlation would be expected.

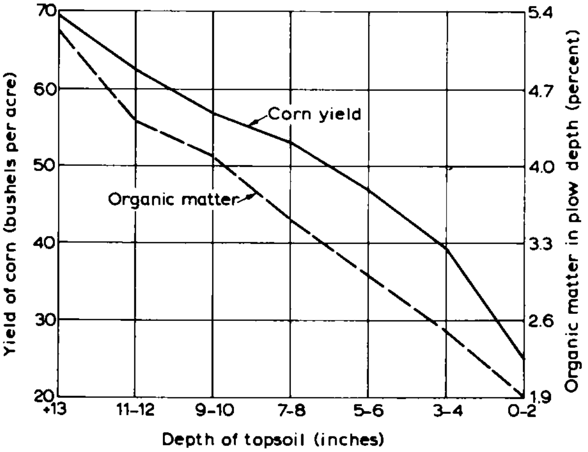

Fig.27.2. Relationship of depth of topsoil and yield of corn, and the percent of organic matter in the top 7 inches (From Uhland, 1949.)

During heavy rainstorms on bare soil the raindrops break up soil aggregates and also tend to free the sand particles from finer material that may be attached to them. Flowing water also helps in this process of disintegration and separation but ordinarily splash erosion is the more important factor, at least on the upper portions of the slope where the soil receives the full force of raindrop impact. The sudden repeated impacts of raindrops can literally tear a soil to pieces and destroy any aggregates that are on the surface.

As flowing water moves over such a soil much of the detached organic matter, clay and silt are floated away. Larger particles are also moved along if the force of the current is strong. As such a soil-laden stream moves along, the coarser materials are deposited at various points where there is a slowing up of water movement and where turbulence has subsided. Most of the heavier particles are, however, dropped at the base of the slope, but the force may be adequate to carry some of them into streams and reservoirs. The organic matter and finest soil particles are the last to be deposited, and may be carried for long distances and be deposited in low lands, reservoirs, or wherever there is no longer an appreciable water movement. In such places this fine sediment may sometimes be several inches thick after a single heavy rain. On drying, it commonly contracts, leaving cracks that may be an inch or more wide. The dark color of these deposits gives ample evidence of their high organic matter content. These deposits, that contain much of the fertility that was at one time located at higher elevations, are commonly very productive in the early stages of erosion. Later, they may be far less fertile if the transported topsoil is buried by sand or by subsoil transported from the higher elevations.

Barrows and Kilmer (1963) have summarized much of the water-erosion data that deal with losses of soil organic matter, nitrogen and phosphorus. It has been shown that eroded soil commonly contains from 1.3 to 4.5 times as much organic matter as the soil remaining on the plots. Although the loss of organic matter depends on the soil losses, the percentage of the humus in the eroded soil decreases as the soil loss increases. This merely shows that when a soil starts to erode, the organic matter tends to float away faster than the mineral matter is transported. Since nearly all of the nitrogen is combined with carbon to form soil organic matter, it is obvious that nitrogen losses closely parallel humus losses in the eroded material. They may slightly exceed organic matter losses if the soil is high in nitrates, or if nitrogen fertilizers have been applied recently. Eroded soil also usually contains more phosphorus than residual soil, because usually 30–65% of the total phosphorus supply is in the soil organic matter. In addition, clay adsorbs this element and the finer soil materials are, like organic matter, very susceptible to erosion if aggregates are absent or are destroyed by raindrop impacts. Doubtless recently-applied phosphorus fertilizers would be subject to adsorption by clays, and even some of the fertilizer itself might be lost if it were applied at the surface and had not yet had time to react with the soil mass.

Experiments conducted on a Collington sandy loam by Martin (1941) showed that eroded material contained 3–8 times as much organic matter and nitrogen as the undisturbed soil. During a period of 2.5 years the pounds of organic matter lost per acre were 1,185 for a fertilized plot, 730 from fertilizer plus rye cover crop, 950 from fertilizer plus 20 tons of stable manure, and 415 from fertilizer plus rye cover crop and 20 tons of manure.

In erosion studies with a loamy sand containing about 16% silt and clay, Neal (1944, 1953) reported that the eroded material contained 58% of these size fractions. It also contained 5 times as much organic matter and nitrogen, 3.1 times as much P_2O_5, and 1.4 times as much K_2O as present in the undisturbed surface soil. Obviously, severe erosion from this type of soil would reduce productivity at a rapid rate.

Analytical data for runoff samples from experimental plots at four locations in

Wisconsin, reported by Massey and Jackson (1952), show that on the average the eroded material contained 2.1 times as much organic matter, 2.7 times as much nitrogen, 3.4 times as much available phosphorus and 19.3 times as much exchangeable potassium as did the main soil mass.

Erosion is particularly damaging to recently-cultivated soils that have no vegetative cover and where contour farming is not practiced. Much attention is now being given to farming systems that protect soil against raindrop impact, and decrease the velocity of the runoff water.

WATER EROSION CONTROL

Organic matter in the forms of soil humus, crop residues, and growing crops are all essential for the control of erosion by both water and wind (Bennett, 1939; Neal, 1953; Stallings, 1957; Zing and Whitfield, 1957; McCalla and Army, 1961; McCalla et al., 1962). The extent and method of use of these kinds of organic matter vary widely with the kind of soil, its slope, climatic conditions, the purpose for which the soil is being used, and many other factors. In fact, the first need is for a land use capability survey that will show how a given area should, and should not, be used, and also give specific practices that may be expected to minimize erosion and lead to efficient crop production. The main erosion control methods, suitable for use on cultivated land, are discussed briefly below. More thorough treatment of the subject is given by Stallings (1957), Smith and Wischmeier (1962) and Chepil and Woodruff (1963).

Although only two forces are involved in water erosion of soils, namely the energy of the falling raindrop and that of surface flow, the methods of protecting cultivated soils against these forces are many. It is cultivation itself that is responsible for the problems; a soil that is kept covered continually with grass or other dense vegetation is not eroded in more than trace amounts. Organic matter, whether living or non-living, is the key to water erosion control.

Soil aggregation

Soils differ widely in their stability or capacity to resist the impact of the falling raindrop. Even those soils that have high resistance to this force are, nevertheless, affected by it, even if at a slower rate. No exposed soils with considerable amounts of clay and silt can completely resist aggregate destruction and puddling that interfere with infiltration and increase erodibility.

It was pointed out in Chapter 16 that aggregates are formed in soils by physical forces, including wetting and drying, freezing and thawing, and especially by growing roots. Physical forces bring the fine soil particles together in close proximity and these unstable aggregates are stabilized by means of humus degradation products, and by polysaccharides and various other organic substances produced by microorganisms. It is usually in grass sods that the maximum development of aggregates occurs. They are more effective than legumes in bringing about good aggregation (Neal, 1953; Allison, 1968). It is also generally recognized that grasses are far more effective in aggregation than are organic manures, such as farmyard manure, cottonseed meal, or even green manures (Martin, 1944).

Inorganic materials, such as iron and aluminum oxides, amorphous silica and carbonates may also act as binding agents, but present available evidence indicates that under humid soil conditions it is low-weight molecular organic compounds that play the major role.

One defense, therefore, against erosion is to make every feasible effort to provide for good aggregation in fine- and medium-textured soils (see Martin et al., 1955; Harris et al., 1966; and Allison, 1968). This assures that the maximum amount of the rainfall will penetrate into the soil, and it also increases the resistance of the soil to the energy of raindrop impact. Well-aggregated soils can resist most of the kinetic energy of the raindrops that fall during showers of low intensity, and also lessen damage caused by heavy rains. Any curtailment of destruction by raindrops also means that soil runoff is correspondingly reduced.

Protection against raindrops

The only way to prevent all soil erosion is to provide a cover that absorbs all of the force of the falling raindrop (Smith and Wischmeier, 1962). A dense vegetative cover is completely effective, but of course in crop rotation systems such a cover cannot be provided for 12 months of the year. Often the probability of erosion is greatest in the spring when showers are usually heaviest, and when most of the seeding is being done. This has led to the development of many new farming systems designed to provide maximum soil protection compatible with the crops being grown.

The use of a mulch that covers the soil completely is effective in the absorption of raindrop energy and in preventing most horizontal flow of water. But mulching materials are scarce, and the mulching system is expensive and not adaptable to all crops.

Studies of Nebraska soils, made by Duley (1939), showed that the condition of the soil surface is the main factor involved in the intake of water. He states that the thin layer that forms on the surface of bare soils during rains had a greater effect on water intake than did soil type, slope, moisture content, or profile characteristics. A high rate of intake of water was attained by the maintenance of a cover of crop residue on the surface.

The stubble-mulch system is a variation of the complete mulch system (see Chapter 25). Such a mulch seldom covers all of the soil surface, and hence does not absorb all of the raindrop energy. Nevertheless, it is very effective and, furthermore, helps to retard the movement of flowing water. Obviously, the heavier the preceding crop, the better the soil coverage by the mulch is likely to be, and the greater the erosion protection. Any exposed soil may be puddled, but that under the residues is free to absorb water at a rate little affected by the rain. Many experiments have shown that as little as 700 lb. of straw or other residue per acre will reduce soil losses by 50–75%; a ton per acre should reduce the losses by 90–95%.

Many other farming systems, usually designated as minimum tillage methods (Chapter 24), have been developed in recent years that are effective in keeping the soil almost undisturbed and largely covered with crop residues or green vegetation for most of the time. These methods can often be used on comparatively steep slopes either alone or in conjunction with terracing and contour farming. Minimum tillage methods usually disturb only a portion of the soil surface, and even if the disturbed portion is pounded by raindrops, the loosened soil particles do not travel far; nearly all of them are caught and held by the nearby undisturbed soil or vegetative cover.

Terracing

Most of the water that falls onto a soil that does not infiltrate into it readily, or is not held back by vegetation, crop residues or soil depressions, flows away in rills and gullies. As the water moves down the slope during a storm the volume increases rapidly as many rills unite to form gullies. With increase in volume there is also likely to be an increase in speed. The force exerted by the flowing water and the amount of soil transported increase with steepness and length of slope. Terracing is a standard method of reducing the potential damage. This consists of dividing the field into several short slopes, thereby allowing the excess water to move gently to lower levels in short intermittent steps and usually via waterways kept lined with grass vegetation (Blakely et al., 1957).

During the early years of soil erosion research much emphasis was placed on terracing because many workers considered that erosion was due chiefly to flowing water. The full importance of the raindrop impact was not then realized. In more recent years the emphasis has been much more on reduced tillage and continuous plant cover as methods of reducing raindrop splash – the chief cause of erosion. Terraces are still recognized as essential in many hilly lands, if they are to be cultivated, but by reducing or preventing raindrop splash, and thereby increasing infiltration, the need for terraces is reduced markedly.

Terraces may also be constructed so that the soil surface is nearly level and thus especially fitted to retain more of the rainfall by infiltration. In fact, that is often their primary purpose; such a terrace is suited to areas where rainfall is normally deficient rather than in excess, and hence is not primarily for erosion control.

Strip-cropping

Contour strip-cropping consists of the alternation of strips of sod crops with strips of cultivated crops, all planted on the contour across the slope. The sod crop not only stops all raindrop splash erosion on its own area but also, under ideal conditions, catches most of the overflow water from the cultivated strip. This farming system works fairly satisfactorily if the slope is not too steep and the soil has a high infiltration rate. However, even then heavy rains may erode much soil from the cultivated strip and bury portions of the sod area. The cultivated area has no protection against the impact of rainwater except that afforded by the crop growing on it and any crop residues left on the surface. During very heavy storms the runoff often channelizes and the rills and gullies may carry off considerable soil if only to the grass strip below.

It is obvious that strip-cropping has its limitations on many soils and slopes. This system does retard overall erosion, but nevertheless considerable soil moves downhill yearly, although in short stages. Certainly some of the newer minimum tillage systems would often be preferable, or perhaps the latter systems could be combined with strip-cropping to stop erosion almost completely. The slope of the land, nature of the soil, amount and time of rainfall, and the crop, are all very important in choosing the best farming system. Under many conditions the best practice is to avoid all cultivated crops and keep the area in grasses or legume-grass mixtures.

Where the slope is very moderate, both terraces and strip-cropping may be avoided by merely planting the cultivated crops on the contour. Most of the rainfall is thus caught and held in place until sufficient time has elapsed for it to sink into the soil. This practice conserves moisture but of course does not completely protect against raindrop energy. Adequate drainage may also be difficult to provide under many conditions.

WIND EROSION PROCESSES

Soil characteristics

Erodibility of bare soils by wind is influenced by soil texture and the extent to which the different-sized particles are held together as aggregates and stable clod structures. According to Chepil (1957), the coarsest- and often the finest-textured soils are more erodible than medium-textured soils because of poor clod development. Coarse-textured soils have insufficient silt and clay to hold erodible sand grains. Fine-textured soils may have too much clay; clods form but these may disintegrate under freezing and thawing into finely-granulated, erodible units. A clay content of 20–30%, together with considerable silt in the 0.005–0.01 mm size, tends to form stable clods.

Water-stable aggregates, or single grains greater than about 1 mm in diameter, are resistant to wind action and abrasion. Any treatment that produces aggregates smaller than this is likely to increase wind erodibility. Wind commonly acts like a sieve in that it removes fine particles and leaves the coarser ones.

Mechanisms of wind action

Soil movement by wind action is a complicated process and influenced by many factors. Chepil (1957), Stallings (1957) and Chepil and Woodruff (1963) give detailed accounts of the principal forces involved and factors affecting them, but these technical details need not be repeated here. Soil particles are subject to movement by saltation, surface creep and by suspension in the air. Usually the three types of movement operate simultaneously but to widely different degrees under different conditions. Chepil states that between 50 and 75% of the weight of the eroded soil is carried in saltation, from 3 to 40% in suspension, and 5 to 25% in surface creep.

Saltation refers to the jumping or bouncing of particles as they are moved along by the wind. According to Stallings, the particles that are so moved consist chiefly of grains having diameters of 0.1–0.5 mm. Most of this bouncing of particles occurs within a foot or less of the soil surface. It is the gusty turbulent winds that lift and spin these particles, and carry them along for an instant until they fall back against the soil surface. The impact of these particles then serves to loosen more particles, and to disintegrate soil aggregates. In some respects the result is similar to that of raindrop splash. As more and more particles are detached from the surface the damage caused by the bouncing action is intensified. The finer particles (less than 0.1 mm in diameter) are too light to be bounced back onto the soil surface, but if the wind velocity is sufficiently strong are carried away.

The detachment of soil particles from bare ground, and their forward movement, increase toward the leeward side of an eroding area. On the windward side, where erosion begins and where the soil is not bombarded by bouncing particles, wind produces almost no movement of particles. This shows that the saltation process is the major one governing wind erosion; without it, most soil particles would remain in place.

Soil movement by surface creep involves the particles that are bounced along in saltation, and also larger particles that are moved along by the impact of these bouncing particles. With each bounce, the soil particles that are small enough to be lifted by the wind jump upward for a few inches and then return to the soil surface a short distance from their previous resting place. Stallings states that the forward movement is about four or five times the vertical distance to which the particle is elevated. These bouncing particles can, therefore, by repeated bouncing move forward fairly rapidly, but the heavier particles can only creep because they are dependent on saltation for energy for forward movement.

Soil particles that are smaller than about 0.1 mm in diameter can be carried along by strong winds for great distances in true suspension. It is primarily the impact of the bouncing particles that is responsible for releasing these particles that are light enough to be picked up by the air currents. It is the turbulence of the air that keeps them from falling. The extent to which wind can remove soil as dust from a bare soil is a function of an extremely large number of factors, but especially of texture and conditions of the soil at the surface. A dry, recently-cultivated, fine-textured soil is much more subject to wind damage than is an undisturbed one.

Effect on soil fertility

Severely-eroded soils may have nearly all of the topsoil removed in certain places where the full impact of the wind is exerted, and where there is no protection against such erosion. Since topsoil consists of both small and large particles, the soil as a whole is not removed. Instead, the finer particles are carried away to be deposited at distances of many miles, whereas the coarser sand and gravel are left in place. Particles that are involved in the saltation and surface creep movements are usually moved for short distances until stopped by impediments that slow down wind velocity. These barriers may be growing plants, crop residues, fences or merely unplowed land. Just as in the case of water erosion, the more fertile portions of the soil are lost and the sand and gravel remain. To the extent that fertile soils are buried by less fertile soil there is much damage, but the greatest damage is from the complete loss of much organic matter, clay and silt that are responsible for most of the fertility.

Soil organic matter plays a vital role in the whole process. As an aggregate-binding material it serves to keep the soil from becoming subject to the forces exerted by winds. A well-aggregated soil is not eroded easily. Organic matter in the form of complete vegetative cover can, by preventing saltation, stop aggregate disintegration and reduce wind erosion damage to near zero.

WIND EROSION CONTROL

Nearly all soils are subject to at least some erosion by winds of high velocity when they are dry and unprotected, and once started, the damage is likely to increase. Fine sandy soils are usually most readily transported as is very obvious to one who travels along the shores of oceans and lakes that are sparsely covered with vegetation. In many places along the Atlantic coast, for example, sand dunes cover many acres and obscure the view of the ocean from those driving along coastal highways. Such dunes are likely to be highest near the ocean, but there are usually many smaller ones extending for considerable distances on the land side. Stabilization of such sandy areas depends upon the growth of grasses, shrubs and trees.

Peat and muck soils are very subject to blowing if and when they become very dry. Mineral soils vary markedly in their susceptibility to wind movement but sandy loams are likely to be readily moved when dry and bare. Clay soils are moved less readily if tightly held as clods that produce surface roughness. Clay soils also hold more water, and wet soils are not much affected by the wind. If clay soils are dry and dusty the surface layer is easily carried away by the wind.

There are many interrelated systems of control of wind erosion that vary widely with soil and climatic conditions. A practice that gives excellent results one year may be unsatisfactory another year on the same area. Stallings (1957) discusses many of the variables encountered and gives practical methods of counteracting wind velocities. Some of the more important control methods are discussed briefly below.

Growing crops

The perfect way to prevent wind erosion, just as is true of water erosion, is to keep the soil covered at all times with a dense mass of vegetation, preferably a sod crop (Salter, 1952). But cultivated crops and not sod crops are usually wanted. This means that as a practical matter we must in many cases settle for methods that are less than 100% efficient. However, in many regions where the yearly rainfall is not over about 20 inches per year, and where cultivated crops grow very poorly, it has been observed that the only practical solution is to return such areas to native grasses or other sod crops that can grow under such conditions. Attempts to grow other crops in such areas may meet with success during the years of highest rainfall, but invariably a droughty year will occur when the crop fails and wind damage becomes severe. This is what happened in the 1930s in the Great Plains region of the United States.

In regions of somewhat higher rainfall, small grains and crops of the sorghum family are the most suited of the cultivated crops. Any row crops should be planted either at right angles to the prevailing winds, or on the contour if this system is used. If the rainfall is somewhat higher, green manures or cover crops may sometimes be used for soil protection, but this is seldom a practical way of maintaining a vegetal cover in dryland regions. Strip-cropping, preferably on the contour, also serves to reduce wind erosion by limiting the distance that soil can move and also by conserving water. When clean-tilled crops that provide little protection are grown, strip-cropping with grasses, and possibly sorghum or cowpeas, are essential and effective. In all cropping systems involving the growth of cultivated crops, care must be taken to keep the residues on the surface for the maximum length of time. Some minimum-tillage systems, now used increasingly to combat water erosion, may also be used with modifications to decrease wind erosion.

Crop residues

The second best method of controlling wind erosion is via crop residues (Chepil, 1955). Under ideal conditions such residues can prevent nearly all erosion. It is essential that the residues be present in adequate amounts for the entire year, or at least for the periods when the cultivated crop is giving poor coverage and the soil would otherwise be nearly bare. It is also important, as pointed out in Chapter 25, that the residues be anchored to the soil, otherwise a considerable portion of them may be blown away. Anchoring is best accomplished by merely leaving much of the straw stubble or other residues undisturbed at the time of harvest. If a portion of the stubble remains standing, and a portion is scattered on the ground, the protection afforded per unit of residue is actually increased over anchored stubble alone.

Chepil (1957) states that the amount of vegetative material required to protect against wind erosion depends primarily on surface roughness, degree of cloddiness, size of field, and strength of the wind. Five hundred pounds per acre of air-dry wheat stubble may be adequate on slightly erodible soil, one ton on moderately susceptible soil, and at least 4 tons on very erodible dune material. The effectiveness per unit of added material decreases as the amount added increases.

Poorly-anchored residues can often be held in place by allowing weeds to grow up through them. In other cases, narrow strips of grain, seeded at right angles to the winds, help materially in reducing the erosion hazards. In some cropping systems the best practice consists in leaving the residues on the surface and then seeding the next crop through or under these residues. The new crop then anchors the residues and provides new residues at harvest time.

When soils are well aggregated and remain in this condition they are somewhat less subject to wind erosion than are poorly-aggregated ones. However, a high level of thoroughly-decomposed crop residues (humus) may, according to Chepil and Woodruff (1963), increase soil erodibility. They state that a high humus content of the soil must, nevertheless, be maintained because the beneficial effects on soil fertility far exceed the detrimental effect on erosion. It is anchored vegetative cover on the soil surface, and not just organic matter, that is essential in soil stabilization.

Whether well-decomposed crop residues tend to increase or decrease wind erosion would be expected to depend on the kind of residue, the nature of the decomposition products, and their chemical and physical reactions in the soil. Certainly, very woody, low-nitrogen, residues would be expected to remain largely detached from the mineral fraction of the soil and, like peat, be susceptible to removal by winds if sufficiently light in weight. Any polysaccharides or humus breakdown products that act as cements in aggregate stabilization would help to hold the soil in place. The remainder of the humus that reacts with colloidal clays to form organic–inorganic complexes would doubtless decrease wind erosion; at least there is little reason to expect that this organic fraction would increase it.

Windbreaks

In regions where the soil moisture is adequate to support tree growth, they can be used effectively to reduce wind velocities and soil erosion. In humid regions the trees may be planted according to a pattern that gives maximum soil protection, but in drier regions the plantings must usually be made where soil moisture is most plentiful. This is likely to be along roadways, drainage ditches and in low places.

A good practice is to plant a row of tall-growing trees with low-growing trees or shrubs on either side and between the taller trees. Where moisture is adequate, this type of planting gives a very effective wind barrier within a few years. Such a windbreak will give considerable protection on the leeward side for a distance of 800 ft. or more, and also serve as a snow-collecting barrier during the winter months. Tree windbreaks are usually very effective in protecting peat and muck soils and can be planted in the most effective places, since moisture is seldom a factor in regions where such soils are found. Where temporary windbreaks are needed, annual crops such as small grains are sometimes used.

CROPPING SYSTEMS AND EROSION

It has been brought out above that under conditions where either water or wind erosion is likely to be a serious menace to a permanent and profitable agriculture, the key to the solution of the problem rests primarily with the crops chosen and how they are grown. Organic matter, whether in the form of green vegetation, root and top residues, or as humified materials, plays important roles in helping to hold the soil in place.

In the case of the growing crop, its effectiveness is dependent on whether it is dense enough to absorb the energy of raindrops and running water, and on whether it is present at the time when eroding storms are likely to occur. A continuous plant cover is required to stop all, or nearly all, erosion, and this may necessitate the use of catch or cover crops where annual crops are being grown. In fact, it is usually impossible to keep a heavy green cover on the soil at all times unless perennials are grown.

The amount of rain that is intercepted by vegetation and evaporated without reaching the soil is greater than is generally supposed. Tisdale and Nelson (1966) cite the work of Wollny, who reported that with a population of 12,700 corn plants per acre, only 60.7% of the total rainfall penetrated the vegetative canopy; with 28,500 plants the corresponding value was 44.5%. Similar figures for soybeans were 78.2 and 64.3%, respectively. Other studies (Enlow and Musgrave, 1938) have indicated that as much as a half inch of rain may be retained upon the leaves and stems of a heavy growth of alfalfa or clover; grass is nearly as effective. Frequent light rains should lead to a high-percentage interception of water by the vegetative canopy, but the percentage intercepted should decrease as the total rainfall increases. Interception would increase as the density of the canopy increases.

The crop also determines to a considerable extent the rate of infiltration into a soil, and thus indirectly the amount of water that is free to run off. Unless the slope of the land is unusually steep, very little water is lost from sod crops. The loss from annual cultivated or uncultivated crops may amount to 20% or more during very hard storms, even though the vegetative cover may be adequate to intercept the raindrops.

Crops can also play a major role in reducing erosion through the kind and amount of residues that they produce. Dense masses of roots that remain in the soil, as well as the tops that are left on the surface, can be handled so as to be effective in minimizing both raindrop erosion and channelization of the water. If incorporated into the soil the residues are the source of the organic compounds that serve to stabilize aggregates being formed by root action.

The effectiveness of grass-legume sods in reducing erosion was shown in simulated rainfall experiments conducted by Mannering et al. (1968). They found that the infiltration rates for first- and second-year corn after grass-legume meadow were 32 and 26% greater, respectively, than for continuous corn. Soil losses for successive years after meadow were 53, 83, 90, and 97%, respectively, of that from continuous corn. Infiltration was 17 and 18% greater and soil losses were 40 and 32% less for corn after 2 and 3 years of meadow than after one year of meadow. Increased soil aggregation was responsible for both increased water intake and reduced soil detachment and transport.

Much emphasis has been placed on the importance of good soil aggregation in soil stabilization, and justly so, but it is well to bear in mind that forests provide near-perfect erosion protection even though these soils are usually almost devoid of aggregates. Not only does the forest canopy hold back much of the rain and absorb the raindrop energy, but the litter on the forest floor absorbs essentially all of the water that falls on it. Thus the soil is protected by both living and dead vegetation. The ground cover of decaying leaves and twigs acts as a sponge that absorbs all of the water that reaches it, and later releases it slowly either to the underlying soil or to the runoff. Under ideal conditions there is no opportunity for appreciable flooding or erosion, even on steep slopes, and a continuous regulated water supply is provided for lower-lying areas. The forest canopy and litter, by preventing rapid runoff, allow sufficient time for the soil to absorb much of the rainfall even though the rate of absorption by such a non-aggregated soil may be slow. If deforestation occurs, most podzols will undergo unusually rapid erosion, chiefly because of lack of aggregation; in contrast, newly-broken grassland soils are usually resistant to erosion for two or more years after they are no longer protected by growing grass.

A soil that is cropped and heavily mulched with straw or other suitable plant material is protected from erosion in much the same manner as are forest soils. There is no raindrop splash and little if any runoff. Such soils are nearly always well aggregated and capable of rapidly absorbing any water that reaches them. Where the mulch is thin, as in stubble-mulch farming, there is less protection of the soil but the water is held back long enough for most of it to infiltrate into the soil.

The system of shifting cultivation, practiced in many parts of the Tropics, prevents erosion in much the same manner as do forests, except that much of the litter is eliminated by burning. The main protection is from the trees and bushes that occupy the area more than 90% of the time. Under tropical conditions vegetation grows so rapidly that no cleared area remains barren for more than a few days or weeks.

Some of the minimum tillage methods that are becoming popular in the United States are highly effective in erosion control. For row crops that are suited to this type of culture, the soil is disturbed very little and the crop residues remain in place. This system favors good aggregation, high infiltration, minimum runoff, and little loss via winds.

In studies reported by Jones et al. (1968), corn was grown under a no-tillage system in comparison with conventional tillage. In the no-tillage system sod was killed, either by using black plastic or by spraying with atrazine, and left undisturbed. During a 6-year period the yields from no tillage were comparable to or ranged from 18–39% above yields from conventional turnplow tillage. The dead sod mulch was very effective in reducing both evaporation and runoff (see also Bickers, 1967).

Phillips (1968) grew cotton with minimum seedbed preparation and reported that the yields were as high as from conventional treatments, provided weeds were kept under control. Admittedly, weed control often constitutes a serious problem in this farming system.

In Melsted's (1954) discussion of the new management practices that are now so common, he pointed out that the aim is maximum crop production with a minimum of soil deterioration. He stated that "the philosophy is based on the concepts that high production is good for the soil, that minimum tillage promotes soil tilth and conserves soil organic matter, that high fertility promotes high yields and lessens the losses of soil humus, that large amounts of decomposable organic matter in the soil are essential to good soil tilth and good physical conditions, and that cover in the form of both living and trash mulches is good protection against all forms of erosion."

Contour farming and strip-cropping, already discussed, serve useful purposes on rolling land but are only partially successful in holding the soil in place. To the extent that sod crops, stubble-mulching, minimum tillage and herbicides can be introduced into contour and strip-cropping systems to reduce tillage, the less will be the soil losses.

Drullinger and Schmidt (1968) call attention to the serious wind erosion problems encountered in the Great Lakes region where sandy soils, peats and mucks, and even some silt and clay loams high in organic matter, are subject to severe wind erosion. The prime concern here is the erosion that occurs on intensively-farmed soils. The mineral soils are cropped largely to corn, beans, sugar beets, tomatoes and potatoes. The organic soils are used primarily for producing high-value truck crops. Soil blowing under the best management systems is being controlled fairly satisfactorily by the use of one or more of the proven practices that include strip-cropping, cover crops, windbreaks, maintenance of stubble mulches, minimum tillage, and irrigation.

Baver (1951) in his discussion of soil erosion emphasizes that this is primarily a problem in farm management. If appreciable erosion does continue regardless of the management system being used, this serves as vivid evidence that the soil is not being used according to its natural capabilities.

Peterson (1964) also points out that soil and water losses from sloping lands decrease as soil fertility and crop yields increase. This is attributable to more rapid early growth, more lush canopy, larger root systems, more organic residues, more active soil flora and fauna, higher organic matter content, and better tilth. Essentially the same ideas were expressed earlier by Truog (1950).

Such rapid advancements have been made in all phases of agriculture during the past 50 years that there is now no longer a logical or sensible reason for excessive erosion to occur. If the soil is very hilly, or otherwise unfit for the growth of cultivated crops, then the best and most profitable practice is to use it for the production of sod crops, fruit crops or forests. All other normal soils can be successfully cropped with a minimum of erosion using methods that have been barely outlined here. Whatever the details of the methods used, the first requirement is that major attention be given to the establishment and maintenance of a high level of soil fertility. High fertility means high crop yields, more protection from rain, and more organic residues that on being returned to the soil assure good aggregation and tilth. Soils respond well to good feeding, proper care and intensive use. Abundant applications of fertilizers to badly-eroded soils, or to others of low fertility, is usually a first requirement in bringing them back to profitable crop production and keeping them in this state.

Although good methods of controlling erosion have been developed, there still remains the economical side of the problem. Even many of the better farmers will not use these methods, or to only a limited extent. This is commonly because they are more interested in the returns for next year and the year thereafter than they are in longtime planning. Row crops usually bring in higher incomes than do sod crops, and hence the tendency is to keep too large a percentage of the tillable area in such crops. The result is that during critical periods of the year there is inadequate vegetative cover. In many instances terracing might help materially in reducing erosion but the cost of construction may be prohibitive in a short-time plan; the returns are likely to be greater if the same amount of money is invested in fertilizer. Under these conditions, where too much of the land is kept in row crops, the annual soil losses are likely to exceed those that conservationists would consider allowable. This is what is happening today in many regions. Eventually the loss in soil fertility may force a change to the use of better conservation practices but it is to be hoped that the changes will be made while the soil is still highly productive rather than later. The wider adoption of minimum tillage methods, where feasible, together with contour farming, should help to reduce erosion even where row crops predominate. If extensive terracing is required, perhaps some sort of a federal subsidy program may be necessary to serve as an incentive for their construction. Such a step could be justified on the basis of the fact that fertile soils are a very important national asset that must be preserved at all costs.

REFERENCES

Allison, F.E., 1968. *Soil Sci.*, 106: 136–143.
Barnett, A.P., Rogers, J.S. and Cobb Jr., C., 1960. *Ga. Agric. Res.*, 1(4).
Barrows, H.L. and Kilmer, V.J., 1963. *Adv. Agron.*, 15: 303–316.
Baver, L.D., 1951. *Soil Sci. Soc. Am., Proc.*, 15: 1–5.
Bennett, H.H., 1939. *Soil Conservation.* McGraw-Hill, New York, N.Y., 993 pp.
Bickers, J., 1967. *Farm J.*, April 1967: 34, 49.
Blakely, B.D., Coyle, J.J. and Steele, J.G. 1957. In: *Soil – Yearbook of Agriculture, 1957.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., pp. 290–307.
Chepil, W.S., 1955. *Soil Sci.*, 80: 413–421.
Chepil, W.S., 1957. In: *Soil – Yearbook of Agriculture, 1957.* U.S. Dep. Agric.,, U.S. Govt. Printing Office, Washington D.C., pp. 308–314.
Chepil, W.S. and Woodruff, N.P., 1963. *Adv. Agron.*, 15: 211–302.
Drullinger, R.H. and Schmidt, B.L., 1968. *J. Soil Water Conserv.*, 23: 58–59.
Duley, F.L., 1939. *Soil Sci. Soc. Am., Proc.*, 4: 60–64.
Enlow, C.R. and Musgrave, G.W., 1938. In: *Soils and Men – Yearbook of Agriculture, 1938.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., pp. 615–633.
Harris, R.F., Chesters, G. and Allen, O.N., 1966. *Adv. Agron.*, 18: 107–169.
Jones, J.N., Moody, J.E., Shear, G.M., Moschler, W.W. and Lillard, J.H., 1968. *Agron. J.*, 60: 17–20.
Langenkamp, R.D., 1965. *The Orange Disc.* Gulf Oil Co., Pittsburg, Pa., 16: 1.
Lowdermilk, W.C., 1953. *U. S. Dep. Agric. Inf. Bull.*, 99: 1–30.
McCalla, T.M., Army, T.J. and Whitfield, C.J., 1962. *J. Soil Water Conserv.*, 17: 204–208.
McCalla, T.M. and Army, T.J., 1961. *Adv. Agron.*, 13: 125–196.
Mannering, J.V., Meyer, L.D. and Johnson, C.B., 1968. *Agron. J.*, 60: 206–209.
Martin, J.P., 1941. *Soil Sci.*, 52: 435–443.
Martin, J.P., Martin, W.P., Page, J.B., Raney, W.A. and De Ment, J.D., 1955. *Adv. Agron.*, 7: 1–37.
Martin, W.S., 1944. *Empire J. Exper. Agric.*, 12: 21–32.
Massey, H.F. and Jackson, M.L., 1952. *Soil Sci. Soc. Am., Proc.*, 16: 353–358.
Melsted, S.W., 1954. *Adv. Agron.*, 6: 121–142.

Neal, O.R., 1944. *J. Am. Soc. Agron.*, 36: 601–607.

Neal, O.R., 1953. *Adv. Agron.*, 5: 383–406.

Peterson, J.B., 1964. *J. Soil Water Conserv.*, 19: 15–19.

Phillips, R.E., 1968. *Agron. J.*, 60: 437–441.

Salter, R.M., 1952. *J. Soil Water Conserv.*, 7: 163–170, 198.

Smith, D.D. and Wischmeier, W.H., 1962. *Adv. Agron.*, 14: 109–148.

Stallings, J.H., 1957. *Soil Conservation.* Prentice-Hall, Englewood Cliffs, N.J., 575 pp.

Tisdale, S.L. and Nelson, W.L., 1966. *Soil Fertility and Fertilizers.* Macmillan, New York, N.Y., 2nd ed., 694 pp.

Truog, E., 1950. *J. Soil Water Conserv.*, 5: 180–185, 194.

Uhland, R.E., 1949. *U.S. Dep. Agric. Publ.*, SCS-TP-75: 1–27.

Wischmeier, W.H. and Mannering, J.V., 1969. *Soil Sci. Soc. Am., Proc.*, 33: 131–137.

Zing, A.W. and Whitfield, C.J., 1957. *U. S. Dep. Agric. Tech. Bull.*, 1166: 1–56.

Chapter 28

ORGANIC FARMING

INTRODUCTION

The designation "organic farming" that I have given to this chapter is sometimes referred to as humus farming, more often as organic gardening, or as the organic movement. What is this organic movement? It consists of the numerous poorly-organized, and unorganized, groups of individuals scattered over the world who are greatly concerned about many of our modern systems of farming, that they claim produce food that is low in nutritive values and conducive to poor health. The organic movement is in short a rebellion against the use of many, or most, of our modern methods of crop and food production, especially of chemical fertilizers. The movement is sometimes described as a philosophy of life.

Jacks (1959) in his review of Jenks' (1959) book characterizes the movement as follows: "The philosophy, however, embraces far more than a denial of the value of chemical fertilizers, which is the part of it that chiefly concerns and usually annoys soil scientists. It is a belief in the wholeness or oneness of Nature, of which man is an integral part except when he uses for the production or destruction of life the artefacts developed by urban industry which is considered to be against Nature. The organic movement holds that the balance of life is sacred and must be preserved when man becomes the ecological dominant. The soil, holding a key position in the balance of life, demands special attention, and it is believed that all measures to introduce non-living amendments such as fertilizers or pesticides that may upset the balance of life either positively or negatively are fraught with danger. The organic movement believes that the wholesale and increasing use of chemicals in agriculture will so destroy the balance of life that civilization itself may founder." He states further that "it is a tremendous faith, honestly held, and it claims to have among its adherents some of the best farmers in the world. But its postulates cannot stand up to scientific analysis, and . . . . . the organic movement has little chance of general acceptance."

IDEAS OF SIR ALBERT HOWARD

The organic movement owes its origin primarily to the work and inspiration of Sir Albert Howard (1931, 1940). Howard was a botanist and plant pathologist who worked in the West Indies, India, and Great Britain. It was in India that he developed the Indore process for the manufacture of compost from vegetables and animal wastes. It was during this time that he formulated and emphasized most of the views that were accepted later by those who became active in the organic movement. Apparently in India he was too isolated from the laboratory and from the tremendous scientific advances being made elsewhere during his lifetime to appreciate that most of his ideas were out of step with reality even before he expressed them. I refer not to his composting process, which was satisfactory if not very original, but rather to his general outlook on agriculture, agricultural methods, and the important role of scientific research.

There is no better way to present Howard's views than to quote extensively from his book, entitled *An Agricultural Testament*, in which he laments the shift from nature's methods of crop production to the newer artificial methods, which he claims lead to the loss of soil fertility. As soil fertility decreases, according to Howard, there follow the many other effects involving increased plant disease and insect damage, poor food quality for animals and man, and a marked deterioration in health. Especially surprising is his severe criticism of agricultural research methods, since he was a botanist engaged in research. Quotations from Howards's book follow.

"The Industrial Revolution, by creating a new hunger – that of the machine – and a vast increase in the urban population, has encroached seriously on the world's store of fertility. A rapid transfer of the soil's capital is taking place. This expansion in manufacture and in population would have made little or no difference had the waste products of the factory and the town been faithfully returned to the land. But this has not been done. Instead, the first principle of agriculture has been disregarded; growth has been speeded up, but nothing has been done to accelerate decay. Farming has become unbalanced. The gap between the two halves of the wheel of life has been left unbridged, or it has been filled by a substitute in the shape of artificial manures. The soils of the world are either being worn out and left in ruins, or are being slowly poisoned. All over the world our capital is being squandered. The restoration and maintenance of soil fertility has become a universal problem."

Howard states further that "the slow poisoning of the life of the soil by artificial manures is one of the greatest calamities which has befallen agriculture and mankind. The responsibility for this disaster must be shared equally by the disciples of Liebig and by the economic system under which we are living. The experiments of the Broadbalk field showed that increased crops could be obtained by the skilful use of chemicals. Industry at once manufactured these manures and organized their sale.

"The flooding of the English market with cheap food, grown anywhere and anyhow, forced the farmers of this country to throw to the winds the old and well-tried principles of mixed farming, and to save themselves from bankruptcy by reducing the cost of production. But this temporary salvation was paid for by loss of fertility. Mother earth has recorded her disapproval by the steady growth of disease in crops, animals, and mankind. The spraying machine was called in to protect the plant; vaccines and serums the animal; in the last resort the afflicted live stock are slaughtered and burnt. This policy is failing before our eyes. The population, fed on improperly grown food, has to be bolstered up by an expensive system of patent medicines, panel doctors, dispensaries, hospitals, and convalescent homes. A C_3 population is being created.

"The situation can only be saved by the community as a whole. The first step is to convince it of the danger and to show the road out of this impasse. The connexion which exists between a fertile soil and healthy crops, healthy animals and, last but not least, healthy human beings must be made known far and wide. As many resident communities as possible, with sufficient land of their own to produce their vegetables, fruit, milk and milk products, cereals, and meat, must be persuaded to feed themselves and to demonstrate the results of fresh food raised on fertile soil. An important item in education, both in the home and in the school, must be the knowledge of the superiority in taste, quality, and keeping power of food, like vegetables and fruit, grown with humus, over produce raised on artificials. The women of England – the mothers of the generations of the future – will then exert their influence in food reform. Foodstuffs will have to be graded, marketed, and retailed according to the way the soil is manured. The urban communities (which in the past have prospered at the expense of the soil) will have to join forces with rural England (which has suffered from exploitation) in making possible the restitution to the country-side of its manurial rights. All connected with the soil – owners, farmers, and labourers – must be assisted financially to restore the lost fertility. Steps must then be taken to safeguard the land of the Empire from the operations of finance. This is essential because our greatest possession is ourselves and because a prosperous and contented country-side is the strongest possible support for the safeguarding of the country's future. Failure to work out a compromise between the needs of the people and of finance can only end in the ruin of both. The mistakes of ancient Rome must be avoided.

"One of the agencies which can assist the land to come into its own is agricultural research. A new type of investigator is needed. The research work of the future must be placed in the hands of a few men and women, who have been brought up on the land, who have received a first-class scientific education, and who have inherited a special aptitude for practical farming. They must combine in each one of them practice and science. Travel must be included in their training because a country like Great Britain, for instance, for reasons of climate and geology, cannot provide examples of the dramatic way in which the growth factors operate.

"The approach to the problems of farming must be made from the field, not from the laboratory ..... the investigator of the future will only differ from the farmer in the possession of an extra implement – science – and in the wider experience which travel confers...... No special organization, for bringing the results of the experiment stations to the farmer, is necessary.

"The administration of agricultural research must be reformed. The vast, top-heavy, complicated, and expensive structure, which has grown up by accretion in the British Empire, must be swept away. The time-consuming and ineffective committee must be abolished. The vast volume of print must be curtailed. The expenditure must be reduced. The dictum of Carrel that 'the best way to increase the intelligence of scientists would be to reduce their number' must be implemented ..... One of the chief duties of the Government will be to prevent the research workers themselves from creating an organization which will act as a bar to progress.

"The base line of the investigations of the future must be a fertile soil. The land must be got into good heart to begin with. The response of the crop and the animal to improved soil conditions must be carefully observed. These are our greatest and most profound experts. We must watch them at work; we must pose to them simple questions; we must build up a case on their replies in ways similar to those Charles Darwin used in his study of the earthworm. Other equally important agencies in research are the insects, fungi, and other micro-organisms which attack the plant and the animal. These are Nature's censors for indicating bad farming. To-day the policy is to destroy these priceless agencies and to perpetuate the inefficient crops and animals they are doing their best to remove. To-morrow we shall regard them as Nature's professors of agriculture and as an essential factor in any rational system of farming. Another valuable method of testing our practice is to observe the effect of time on the variety. If it shows a tendency to run out, something is wrong. If it seems to be permanent, our methods are correct. The efficiency of the agriculture of the future will therefore be measured by the reduction in the number of plant breeders. A few only will be needed when soils become fertile and remain so.

"Nature has provided in the forest an example which can be safely copied in transforming wastes into humus – the key to prosperity. This is the basis of the Indore Process. Mixed vegetable and animal wastes can be converted into humus by fungi and bacteria in ninety days, provided they are supplied with water, sufficient air, and a base for neutralizing excessive acidity. As the compost heap is alive, it needs just as much care and attention as the live stock on the farm; otherwise humus of the best quality will not be obtained."

Howard also held the opinion that the mycorrhizae found on the roots of many trees and cultivated crops play an important role in plant nutrition and in protection of the plant against disease. He states that "the utilization of humus by the crop depends partly on the mycorrhizal association – the living fungous bridge which connects soil and sap. Nature has gone to great pains to perfect the work of the green leaf by the previous digestion of carbohydrates and proteins. We must make the fullest use of this machinery by keeping up the humus content of the soil. When this is done, quality and health appear in the crop and in the live stock." He forecast that "at least half the illnesses of mankind will disappear once our food supplies are raised from fertile soil and consumed in a fresh condition."

In his discussion of the restoration of soil fertility, Howard pleads for the return of all wastes to the soil, chiefly via the compost pile. He emphasizes, especially, the return of the urine of animals, farm-yard manure, and also night soil. According to him, urine is so valuable because "it contains in a soluble and balanced form all the nitrogen and minerals, and in all probability the accessory growth-substances as well, needed for the work of the fungi and bacteria which break down the various forms of cellulose – the first step in the synthesis of humus. It carries in all probability every raw material, known and unknown, discovered and undiscovered, needed in the building up of a fertile soil. Much of this vital substance for restoring soil fertility is either wasted or only imperfectly utilized. This fact alone would explain the disintegration of the agriculture of the West."

He states further that "the vegetable and animal residues of Western agriculture are either being completely wasted or else imperfectly utilized. A wide gap between the humus used up in crop production and the humus added as manure has naturally developed. This has been filled by chemical manures. The principle followed, based on the Liebig tradition, is that any deficiencies in the soil solution can be made up by the addition of suitable chemicals. This is based on a complete misconception of plant nutrition. It is superficial and fundamentally unsound. It takes no account of the life of the soil, including the mycorrhizal association – the living fungous bridge which connects soil and sap. Artificial manures lead inevitably to artificial nutrition, artificial food, artificial animals, and finally to artificial men and women.

"The ease with which crops can be grown with chemicals has made the correct utilization of wastes much more difficult. If a cheap substitute for humus exists why not use it? The answer is twofold. In the first place, chemicals can never be a substitute for humus because Nature has ordained that the soil must live and the mycorrhizal association must be an essential link in plant nutrition. In the second place, the use of such a substitute cannot be cheap because soil fertility – one of the most important assets of any country – is lost; because artificial plants, artificial animals, and artificial men are unhealthy and can only be protected from the parasites, whose duty it is to remove them, by means of poison sprays, vaccines and serums and an expensive system of patent medicines, panel doctors, hospitals, and so forth. When the finance of crop production is considered together with that of the various social services which are needed to repair the consequences of an unsound agriculture, and when it is borne in mind that our greatest possession is a healthy, virile population, the cheapness of artificial manures disappears altogether. In the years to come chemical manures will be considered as one of the greatest follies of the industrial epoch. The teachings of the agricultural economists of this period will be dismissed as superficial."

The above lengthy quotations from Howard are given because they state so clearly the fundamental beliefs of those who later have had a part in the organic movement. As the quotations clearly bring out, the movement is not based entirely on the supposed harmful effects of chemical fertilizers; rather as Jacks (1959) states, the movement is a philosophy or protest against the trend of agriculture since the beginning of the industrial scientific age. Many organic gardeners have advocated the ideas of Howard with the vigor and tenacity that others apply to the teachings of a religious cult.

It is surprising indeed that a man of Howard's education and experience should have been so unable to evaluate the events of the time, and to have had such a large percentage of his life work discredited. Even his concepts of how agricultural research should be conducted were as much in error as were his ideas on the detrimental effects of chemicals on soil fertility, food quality and human health.

DEVELOPMENTS SINCE 1940

The present organic movement, according to Jenks (1959), covers the fields of agriculture, nutrition, and health – the common factor linking them being food. In addition to the writings of Howard and Jenks, the ideas of the organic gardeners are presented by Rodale (1946), Balfour (1950), and Hainsworth (1954). Many articles have also been published in the journal *Organic Gardening* (later *Organic Gardening and Farming*), since 1942 and in *Mother Earth* since 1946.

The followers of the organic movement have hewed closely to the line of thinking advanced by Howard. Any appreciable deviations from the agricultural methods practiced prior to the 20th century are likely to be condemned. Chemical fertilizers must not be used since they are claimed to poison the soil, the plants, the livestock, and eventually the health of man who consumes the plant and meat products. Food grown by nature's methods on soils made fertile by compost is considered nutritious and conducive to health if eaten while fresh; in contrast, processed food is deficient, especially in minerals, vitamins, and unknown materials that are essential for good health. Great emphasis is placed on the role of the soil and the need to maintain fertility, but fertility must be maintained strictly by the return of all wastes, chiefly compost, and by the use of mixed cropping systems, much as practiced in the Far East for centuries (see King, 1911). The most condemned form of agriculture is monoculture using chemical fertilizers and various kinds of chemical spray materials for the control of insects, diseases and weeds. The claim of the organic gardeners is that if the natural system of crop production is followed, insects and diseases are kept under control without the use of spray materials.

NATURE OF SUPPORTING EVIDENCE

When an agricultural scientist studies the literature of the organic gardeners, he finds no acceptable proof of their claims. No control tests are reported, and unfavorable reports go unreported. The bias involved in such reporting is so great that such literature is not only worthless but often misleading.

Even more objectionable is the tendency of a few writers to "back up" their claims by frequent references to scientific literature that actually has no bearing on the subject under discussion. Sometimes the results of good scientific experiments are even reinterpreted to fit the claims of the writer, and the conclusions drawn are at variance with the scientific facts as set forth by the scientist. Another characteristic of the organic school is that the followers rarely agree that any of their original claims have been discredited, regardless of the quality of scientific data that refute the claims.

Reference was made earlier to Howard's disagreement with the research methods followed by scientists. He strongly objected to the isolation of single factors, one at a time, for study, regardless of the fact that one of the most basic concepts of scientists is that proof of the importance of any one factor can be obtained only by isolation of that factor under study. Likewise, Balfour states that "soil biologists have tended to focus their attention on specialized groups of soil organisms such as, for example, nitrogen-fixing bacteria, and specific parasitic fungi. They have largely overlooked the general relationship of the soil microflora with normal growth." It seems pertinent to ask how anyone would know whether an organism could or could not fix nitrogen if it were not grown in the laboratory in pure culture. Likewise, how could one know which one of thousands of species of fungi was causing a disease if the causative agent were not isolated and tested for parasitism by inoculation into a plant of the same species?

Balfour states further that "this fragmentation (of research), while understandable, nevertheless seems to me to be the curse of much modern research. Whatever we study, our tendency is to break it up into little bits, thereby destroying the whole, and then to study the effect of behaviour of the separate pieces as though they were independent, instead of – as in fact they are – interdependent." Any scientist would reply to this by pointing out that after we understand the bits, and not until then, are we in position to evaluate the whole with some hope that we arrive at the proper conclusions. Any past delay in agricultural advancement has been due far more to lack of fundamental laboratory data than to lack of practical field observations.

Jenks (1959) devotes a chapter to what he calls the fragmentation of science, and states that the chemical approach has proceeded through such fragmentation. In contrast, the organic approach "seeks to re-direct the attention of science to the unity of Nature, and therefore emphasizes the importance of wholeness, both as a philosophic concept and as an ideal to be sought in practice. It is concerned much less with the attainment of specific objectives and the solution of specific problems than with progress toward a complete and balanced picture of Nature as a basis for more enlightened practice.......

"In the present imperfect state of human knowledge, such an approach must rely to some extent on intuitive reasoning, perhaps even intelligent guesswork. But 'the whole' is so vast, and is still so largely unexplored, that if no allowance is made for what has not yet been reduced to 'facts and figures', there is no alternative but to ignore it altogether – which is, in effect, the attitude of many of those of conventional outlook."

Jenks' statements, made in 1959, were wholly unjustified. The fragmentation of science by scientists has built a solid foundation for the understanding of nature as a whole which could not have been brought about by other methods. Agricultural extension has done an excellent job of tying together the scientific fragments and presenting them to the farmer in a form that he can best use.

In the space available here no attempt will be made to discuss every claim that has been made by the followers of the organic movement, but only some of the more important assumptions that involve the role of organic matter in soil fertility, crop production and human health. Hopkins (1950, 1957) has considered the claims of the anti-fertilizer school. The present writer sees no need to cover the same ground in detail but strongly urges all interested readers to study the evidence as presented here.

THE NON-EXISTENT BIOLOGICAL GAP

The organic movement places great stress on the role of microorganisms in soil. In fact, the followers often give the impression, intentionally or otherwise, that they are almost the only ones who give soil microorganisms any more than a casual thought, or make use of them. One might assume from their writings that there is almost complete lack of biological knowledge on the part of scientifically-trained agriculturalists. As one who majored in this field of science, and spent many subsequent years in such research, I can assure the reader that this concept is completely at variance from the facts.

The sciences of soil microbiology and biochemistry have never lagged appreciably behind that of other fields of agricultural science. In fact, long before there was a chemical fertilizer industry, or an organic movement, most of the main facts regarding the part that microorganisms play in soil fertility had been determined, and the information was being used in crop production to the extent that seemed feasible and practicable at the time. Such subjects as organic matter transformation in soils, nitrification, denitrification, and nitrogen fixation were well understood for at least 30 years before Howard published his book. Even the roles of the individual groups of microorganisms were given attention early. The symbiotic relationship that exists in legume nodules was determined before the end of the nineteenth century.

The importance of soil microorganisms has, admittedly, often received less publicity than have some other fields of soil science, because progress in developing the science often could not be readily publicized in economic terms. Hybrid corn, or a new type of fertilizer, or a new insecticide may produce surprising results immediately. In contrast, a detailed, longtime study of organic matter breakdown by hundreds of species of microorganisms does little more than tell us how it occurs; thousands of years before such studies were made the Chinese were reaping the benefits of the activities of such organisms even without knowing that they existed. Compost prepared by the Chinese 2,000 years ago was probably as good as that prepared by Howard and his followers. In fact, it may have been better if the nutrient content happened to be higher.

Organic gardeners for the most part seem to consider that agricultural scientists are primarily chemically trained and chemically minded, when actually they are often more deficient in chemical knowledge than in the biological sciences. They are strong advocates of the use of chemical fertilizers, but this fact does not indicate that they do not appreciate the importance of soil microorganisms. Rather, they know the limitations of these organisms and the advantages of supplemental applications of plant nutrients. Chemicals plus microorganisms can produce much larger and more nutritious crops than can microorganisms alone. For example, decay processes may be able to produce no more than 100 lb. of available nitrogen per acre during a growing season, but a 100-bushel corn crop requires 200 lb. Does it not make sense to apply supplemental chemical nitrogen so as to obtain a 100-bushel yield rather than only 50 bushels? The extra nitrogen does not deplete soil humus but increases it.

Over-estimation of the role and value of microorganisms can be at least as inexcusable as under-estimation. The outstanding example of such an error is the far-reaching claims made by the organic gardeners with respect to mycorrhizae. This is discussed in Chapter 5 and also in a subsequent section of the present chapter. Likewise, the contribution of nonsymbiotic nitrogen-fixing bacteria to the soil nitrogen supply has often been overestimated (see Chapter 10).

SOURCES OF PLANT NUTRIENTS

Under virgin conditions plants obtain all of their required nutrients from either soil, water, or air. Since carbon, hydrogen and oxygen can be obtained readily from air and water, we are not especially concerned with them at this point. Our chief concern is with nitrogen, phosphorus and potassium, which are the main elements supplied in chemical fertilizers. In addition, are calcium, magnesium, sulfur and the seven micronutrients (see Chapter 14). As a result chiefly of weathering and biological activities, there occurs a continuous cycling of these mineral nutrients; a given quantity of one of these nutrients may be taken up from the soil solution or soil by a growing plant and be returned to the soil when the plant dies and decomposes. Under virgin conditions the cycling may go on indefinitely with only minor losses to the drainage waters and to the air. Under non-virgin conditions where the crop is removed or consumed by livestock, only a portion of the element is returned. The organic movement lays great stress on the return of all crop residues and all animal and human wastes, but even if this is done there is a deficiency of nutrients, and high crop yields are possible under this system only if one land area is built up at the expense of an adjoining one. This is what happens when composts are prepared from materials gathered from various areas but utilized to fertilize a limited acreage.

What are the chemical forms in which the nutrient elements are taken up by plants? Under natural conditions nitrogen is absorbed from the soil solution chiefly as ammonium and nitrate ions. Very small amounts of nitrite and simple organic substances may also be taken up. The source of this nitrogen may be ammonium from rocks, nitrogen gas from the air, or nitrogen compounds released from decaying soil organic matter. Whatever the source of the nitrogen, it is converted by one route or another almost entirely into ammonium and nitrate salts that are the same chemically as the nitrates and ammonium salts found in chemical fertilizers. Considerable urea also finds its way into the fertilizer bag, but on reaching the soil is also quickly converted into ammonia and nitrates.

Plants absorb most of their phosphate as the primary orthophosphate ion but some secondary orthophosphate may also be taken up, depending on the pH of the soil. Unknown but small amounts of organic phosphates, such as nucleic acid, may also be assimilated, but organic phosphates are of minor importance as direct sources of phosphorus. Even though soils often contain a third of their phosphorus in the organic form, it is almost completely unavailable to plants until converted biologically into orthophosphate. The phosphorus in commercial fertilizers is also present almost entirely as orthophosphate.

Potassium is present in most soils in relatively large quantities, chiefly in the forms of comparatively unavailable primary and secondary minerals. As it is slowly released by weathering and by biological activities, the potassium ions may be taken up by plants, combine with any acidic ions present to form salts, enter into the exchange complex, or be fixed in clay minerals. Potassium, supplied as chemical fertilizer, is usually in the forms of sulfates or chlorides. Potassium derived from soil minerals, or from chemical fertilizers, is therefore subject to the same fate and enters the plant in the same forms.

Calcium and magnesium are basic elements that are found in soils as carbonates, sulfates and other inorganic salts. If added as liming materials, or in fertilizers, they are likewise in inorganic forms.

Sulfur is present in soils in organic matter and also as salts of calcium, magnesium, sodium and potassium. When the organic matter decomposes, most of the sulfur is released to form salts. Regardless of the source, it is assimilated chiefly in the form of sulfate ion.

Micronutrients are found in soils either as comparatively insoluble minerals, or as ions sorbed on the soil organic matter. They may be found in fertilizers as impurities, or perhaps in added slowly-available mineral materials. The traces of these materials used by plants are taken up chiefly as ions from the exchange complex.

This brief summary of the sources of plant nutrients shows that, with few exceptions, it makes little difference to the plant what these are; absorption is almost wholly from inorganic salts or as ions being released by weathering or biological action. The soil colloids serve as an excellent medium for holding in available form any ions so released but not immediately taken up by the plant. In the light of these well-established facts, why do the organic gardeners put so much emphasis on the advantages of natural sources of nutrients, especially compost, over nutrients supplied in chemical fertilizers? Obviously, there is no appreciable chemical difference between the two sources. The main difference is in concentrations of salts or ions present, and in the ameliorating or buffering effect of the organic matter supplied as compost or as undecomposed crop residues that are rapidly converted into humus.

This ameliorating or buffering effect, discussed at length in Chapter 15, is important, but soil organic matter maintenance is not dependent upon the exclusive use of compost and manures. As pointed out elsewhere in this book, inorganic fertilizers alone will in many cropping systems maintain or increase soil organic matter levels. Chemical fertilizers, when properly used, seldom if ever produce toxic or poisoning effects on soils, plants, animals or man. Both organic and inorganic sources of nutrients can and should be used as available, and as economically feasible.

THE ROLE OF MYCORRHIZAE

Scientific results

Our knowledge of the nature and role of mycorrhizae is discussed in Chapter 5. It is pointed out there that there are two types, namely ectotrophic and endotrophic, and that they are found widely distributed on the roots of many, perhaps most, plants, including trees, shrubs and cultivated crops. Most of the research reported has been with ectotrophic mycorrhizae that live on the roots of forest trees. It has apparently been established that these fungi are essential for some trees, particularly pines, but there is, as yet, little or no evidence that mycorrhizae play a major role in the nutrition of our common agricultural crops. So far as I know, all of these plant species can be grown satisfactorily under aseptic conditions (without fungi) if the necessary nutrients are supplied.

According to Harley (1965) "there is a fairly wide range of structures grouped under the name of ectotrophic mycorrhizas. Even upon a single host many variants may be found depending upon the conditions or upon the fungal species present. A common central group of these structures are organs of integrated construction which when studied by physiological methods have been found to be efficient absorbing organs with peculiar properties. The extremes of the range depart substantially from the central group in structure and in the degree in which they appear to be integrated functional organs. In many the fungus appears to be parasitic on the host."

Difficulties in the evaluation of mycorrhizae are due in part to the lack of homogeneity with respect to host–parasite relationships, especially among the endotrophic pairs. Many host plants and many fungal species are involved, and ecology plays an important role in determining the relationships that are established and their mutual effectiveness. These symbiotic fungi are dependent upon their hosts for their energy supply, and many of them also for vitamins, amino acids and organic growth substances. In the case of ectotrophic mycorrhizae on some forest trees, and possibly on other plants, there is evidence that this association results in more efficient absorption of nitrogen and mineral salts than where the rootlets are not infected. The explanation may well lie in part in the fact, pointed out by Garrett (1960), that mycorrhizal rootlets probably remain functional for a longer time and are less subject to pathogenic infection. According to Harley (1965), ectotrophic mycorrhizae have a period of activity varying from a few months to about a year. One would expect that activity would be much less for cultivated crops, but data are not available.

There is considerable evidence, although perhaps not conclusive, that the development of ectotrophic mycorrhizae on forest trees is favored by a shortage of inorganic nutrients and depressed by heavy manuring with nitrogen and mineral salts (Harley, 1965). There is uncertainty as to the explanation for this observation, but it has been suggested that the plant level of available carbohydrate is the controlling factor; under normal light conditions the soluble carbohydrate level in the root varies inversely with the supply of available nitrogen.

Host cells on some plants that are infected with mycorrhizal fungi, especially endotrophic organisms, are able by intracellular digestion of the hyphae to keep the infection within bounds. This lends support to the view expressed by Garrett (1960) that the mycorrhizal association is much more a case of controlled parasitism than of symbiosis. Comprehensive generalizations are, however, not justified.

According to Harley (1965), although there is strong evidence that certain forms of mycorrhizal infection of forest trees and orchids are essential to healthy development in some ecological conditions, there are also variants of mycorrhizal structures associated with poor health of the host, showing that such infections merge into parasitism. He states that "forest-tree roots are found in which the cells may be extensively penetrated by hyphae, in which the fungal mantle is deficient or excessively developed, and in which signs of destruction of the host tissue exist. Such rootlets are often unbranched, simple, and have been given the name of 'pseudomycorrhiza'. They may be produced by special fungi which have some of the properties of mycorrhizal fungi but are incapable of setting up a prolonged healthy steady-state condition. Or they may be the products of special environmental conditions acting upon fungus and host which could elsewhere produce integrated healthy mycorrhizal structures. Many hosts may indeed set up a range of associations from destructive parasitism to loose uncoordinated associated growth with various fungi under various conditions. The remarkable fact is, however, that in their natural ecological ambits, hosts and fungi produce efficient, long-lived dual mycorrhizal structures to a dominant degree. Perhaps, since natural selection operates, this is to be expected." It should be emphasized again that this quotation refers to forest trees; we are much in the dark as to the situation that prevails on the roots of cultivated crops.

Harley (1965) also calls attention to mycorrhizae caused by aseptate hyphae, designated as vesicular–arbuscular mycorrhizae, which differ markedly from those found on forest trees. He states that they are extremely common and widespread in the plant kingdom, being almost universally present in seed plants not infected with other kinds of mycorrhizae. The more specialized forms have not been grown in pure culture. Comparatively little is known about the effect of these fungi on the host plant. Infection is usually most intense on poor soils, and such infected plants seem to benefit from it.

The above survey of the present state of our knowledge emphasizes the complexity of the problem, and our limited knowledge of the role of these fungi in plant nutrition, especially in agricultural crops. Some fungi are unquestionably beneficial, or even essential, under some ecological conditions, whereas under other conditions they may have only a limited beneficial effect or occasionally be harmful.

Claims of organic gardeners

Various persons, who have been most active in the organic movement, have placed great emphasis on the importance of mycorrhizae in crop production. This possibility was emphasized by Howard, as mentioned above. He found mycorrhizal fungi on various crop plants, but was most impressed by his observations on tea roots. Where his Indore-process compost was used he found these fungi present in abundance, and since crop yields were increased he concluded that much of the benefit must be attributed to these fungi. In the light of our present knowledge it seems safe to say that his composts increased yields because they supplied available nutrients during the growing season; it is very doubtful if the mycorrhizal fungi played as important a role in the increased crop yields as did the saprophytic fungi and bacteria that released the available nutrients, and remained outside the plant roots.

Balfour devotes most of two chapters to the role of mycorrhizae. Her thesis and arguments are based chiefly on the work of Rayner and Neilson-Jones (1944) with ectotrophic mycorrhizae of pine trees, although she admits that their findings might not be applicable to field crops. In this connection it should be pointed out that the site chosen by Rayner and Neilson-Jones was a poorly-drained, gravelly heather peat not suitable for the growth of general crops. These workers were, in fact, only concerned with its possible use for forestation.

According to Rayner and Neilson-Jones, young trees fertilized with compost formed mycorrhizae, whereas those receiving inorganic fertilizer were free of these organisms and did not make a normal growth. The essentiality of the root fungi seemed to be proven. However, in subsequent work at the Rothamsted Experimental Station, good growths of tree seedlings were obtained where chemical fertilizer only was supplied.

In referring to Balfour's discussion of the findings of Rayner and Neilson-Jones, Hopkins (1957) states that "it must therefore be emphasized that the one basic deduction from that work – that composts succeed where fertilizers failed – has been completely disproved, and that all the other deductions – since they were linked with this one – must be regarded as similarly unsound." In Balfour's 1950 revised edition of her book she left her apparently disproven mycorrhizal hypothesis intact.

PLANT DISEASES AND INSECTS

One of the claims of the advocates of humus farming that is most astonishing to a scientist is that insects and plant diseases are not serious menaces to crop production if all chemicals are excluded from farming operations and nature's methods only are used. Howard laid great emphasis on this point, basing his conclusions on his limited qualitative observations. He did not prove this, and no one else has. Howard's followers merely accepted his claims, and extended and generalized on them.

Balfour summarizes some of the far-reaching claims made by many advocates of humus farming. They are "that if the fertility of the soil is built up with adequate supplies of humus, crops do not suffer from diseases and do not require poison sprays to control parasites; that animals fed on these plants develop a high degree of disease resistance, and that man, nurtured with such plants and animals can reach a standard of health, and a power of resisting disease and infection, from whatever cause, greatly in advance of anything ordinarily found in this country." It would indeed be fortunate if this quotation were fact rather than fallacy.

Hainsworth (1954) in his chapter on disease resistance in plants states in his opening paragraph that "this chapter must of necessity be largely surmise owing to the small amount of research, and that mostly indirect, which has been done on the subject." The same statement applies to our knowledge of the effect of humus on insects.

In an attempt to explain how and if abundant humus discourages disease organisms considerable emphasis is placed on the fact or hypothesis that humus favors the development of mycorrhizae, and that these in turn discourage attacks by pathogenic microorganisms. This is a plausible supposition, but until data are available we must keep the idea in the category of a hypothesis – to explain an unproven claim. At this point one might logically ask why an exceedingly well-nourished and probably succulent plant, grown on a high-humus soil, should not be very susceptible to attack by parasitic microorganisms. In nature the growth of microorganisms is usually directly correlated with available food supply and succulence.

Explanations for the claim that compost additions confer resistance to attack by insects are even harder to find than in the case of diseases, as Balfour admits. She hypothesized "first, that the vigor of growth is so strong in the case of the compost-grown plants, that they are able quickly to repair the ravages of the pest, and secondly, that the compost-grown plant may be more nourishing and the parasite consequently satisfied with less." Neither explanation makes sense, and few scientists will even give them serious consideration. Meanwhile, the search for more and better chemical insecticides will doubtless continue.

In recent years pesticides have received considerable unfavorable publicity and efforts have been made to curtail their use because of their supposedly harmful effects. This development is in most respects unfortunate, for aside from the long-lasting chlorinated hydrocarbons, such as DDT, they are rarely hazardous. DDT is harmful to birds and may upset the food chains and ecosystems, but pesticides other than chlorinated hydrocarbons are decomposed so comparatively rapidly that such effects are not encountered. This presents a challenge to the chemist to produce suitable substitutes for any pesticides that may be questioned.

Bradfield (1954) states that he cannot accept the claims that crops grown with organic fertilizers are free from diseases and insects and more nutritious. He points out that "the potato blight, which destroyed Ireland's potato crop and decimated its population, took place before the widespread use of commercial fertilizers; and wheat rusts have caused famines in areas which have never used the slightest bit of commercial fertilizer. We have had invasions of grasshoppers since Biblical times, and invasions of army worms and Japanese beetles do not discriminate between crops fertilized with organic materials and those fertilized with chemical materials. To a chemist the claim that chemical fertilizers are poisonous and should never be used in food production does not make sense." I might add that in the United States heavy damage was produced on various crops by a variety of insects, prior to the fertilizer era. Furthermore, I know of no evidence that insects such as the cotton boll weevil, potato beetle, Mexican bean beetle, corn borer, corn ear and root worms, chinch bug, and melon beetles refrain from attacking plants that have received no chemical fertilizers. The same statement also applies to plant diseases.

The insect menace is far more real than the public is likely to consider, due in large part to the success that man has realized in insect control by means of insecticides. No plants or animals seem to be immune to insect depredations. These depredations may be the result of direct attack, or the insects may act as vectors of plant and animal diseases. Cazier (1953) estimated that 600 or more injurious insect species of primary importance are known to occur in North America. Losses caused by insects each year in the United States for all agricultural products were estimated by Murphy (1954) to be at least 7–8 billion dollars.

Some insects have a rate of reproduction that is almost unbelievably high. According to Decker (1958), it has been estimated that the total mass of protoplasm produced by insects each year exceeds that produced by all other terrestial animals put together. This vividly shows the magnitude of the problem with which man must deal. Although insects are constantly being attacked or preyed upon by other insects, animals, plant and man, it is obvious that man cannot afford to deny himself the use of chemicals in his fight for survival against the insect hordes. Nature's methods, as advocated by the organic gardeners, are far from adequate, if at all effective.

Murphy (1954) states that "without the benefits of the past 100 years of research in entomology and insect control and the application by the American public of the knowledge gained therefrom our annual per acre yields of crops and livestock probably would be half or less of those of today. In addition, hundreds of thousands would be ill from the diseases insects carry."

Wadleigh (1965) expresses similar ideas and points out the necessity for the use of chemical pesticides, chemical fertilizers, improved varieties of plants and modern mechanical procedures. He states that "the development of agricultural technology so vital in providing man's basic needs for civilized progress never has been, is not now, and never will be in accord with nature."

NUTRITIONAL QUALITY OF PLANTS

Are crops grown according to nature's methods as specified by the organic school more nutritious than those grown on soils receiving chemical fertilizers? Such claims have been made repeatedly by these organic gardeners. This question is answered by research workers at the U. S. Plant, Soil, and Nutrition Laboratory at Cornell University *(U.S.D.A. Agricultural Information Bulletin*, 129, 1965) as follows: "A number of experiments have been conducted to check on this speculation. The nutritional quality of plants grown in soils that have received large amounts of organic manures has been compared with that of plants grown on soils that have received only inorganic fertilizers or, in some cases, with plants grown in culture solutions containing only inorganic salts of the essential elements. Any differences in their content of essential elements or vitamins that have been noted have been too small to be of any nutritional significance, and have been in favor of the inorganic fertilized plants as often as in favor of those grown with organic materials." This agrees with Bradfield's earlier statement that "so far as I have been able to find out, there is no valid evidence to support the nutrition claim."

This finding is in accord with expectations, because the main point is whether the soil contains all of the elements in available form that are required for plant growth. Soils differ widely in their content of essential elements, and the addition of organic materials as compost or animal manure would not necessarily correct any deficiencies, especially since these organic materials are usually derived locally. If obtained from distant sources and other soils, they might help to correct mineral deficiencies, but organic manures are usually returned to the soils that produced them. Where inorganic fertilizers are applied, any known deficiencies can readily be eliminated by addition of the deficient elements in the fertilizer. Because of this possibility, soils that receive chemical fertilizers are likely to be more complete growth media than are those that receive only organics.

When we speak of nutritional quality of plants we are referring primarily to their suitability as food for animals and man. This changes the picture markedly for the needs of animals are not always the same as those of plants. It is also necessary to know whether the plant product is to be used as the sole food of animals, as is common when they are kept on pasture for long periods. If the plant product constitutes only a small part of the ration, then any nutritive deficiencies can readily be supplied from other sources or from manufactured substances. For example, corn that is deficient in lysine is a poor food when used as the sole feed, but with outside sources of lysine there is no problem. Likewise, if cobalt, which is not needed by crops, is deficient in feed products, it can be supplied to ruminants as inorganic salts, or to other animals as vitamin B_{12}.

Agricultural practices have changed markedly since the beginning of the Industrial Revolution. Such changes include not only the use of more chemical fertilizers and spray materials, but more intensive farming, a tendency toward monoculture, new crop varieties, hybridization, closer planting, new cultural systems, new rotations or none, new harvesting methods, introduction of pests from other countries, etc. Obviously, if diseases and insects have increased, which is doubtful as Hopkins points out, it is scarcely logical to place the blame on failure to use compost, especially when the soil humus has usually been maintained in recent years by methods other than the use of compost.

It is well to include a statement of Hopkins (1957) in refutation of the emphasis that the humus school has placed on nature's methods. Nature in the raw is usually a wilderness of trees, shrubs or grasses; or merely miles of desert sands. Hopkins states that "agriculture is fundamentally unnatural, it starts off with unnatural soil treatment and most plants to-day are kinds especially bred for man's own purposes, for the most part long removed from their natural birthplaces and rapidly stepped up in evolutionary changes not by Nature but by man. With such a background, how can anyone lay down rules that accessory actions in cultivation and plant nutrition should be only those kinds of actions which are themselves natural? Indeed, in talking about 'being natural' in agriculture, are we not often merely at verbal cross purposes? To many people nothing could be more 'natural' than a field of potatoes neatly set out in rows. Certainly on a train that leaves the built-up huddles of a city and then runs past potato-fields, the arable crops of farms are comparatively natural; the enormous difference in naturalness between the potato fields and some adjacent permanent grassland or scrub is not so apparent without thought. Natural is a bad word – it has discarded most of its meaning."

The history of the potato plant well illustrates the above statement. Hopkins points out that "the potato was originally a wild Mexican plant. Imported into other climates and soils, new varieties were bred in a perpetual effort to obtain potatoes which could in these new conditions provide bigger crops or earlier crops. It is no good criticizing this procedure – it is, on the whole, the kind of thing man must do to remain the predominant form of life on earth. " Would the organic gardeners suggest that we now discard our improved potato varieties and grow only the original wild type according to nature's methods?

FOOD VALUES AND HEALTH

According to the teachings of the organic school, shown in quotations given above, the supposed bad effects of chemicals and good effects of organics on plant growth, extend over to the animals and man who consume them. Balfour devoted several pages to her attempt to prove that animal and human health are dependent upon how the plants are grown that serve as food sources. Citations of isolated, selected, qualitative observations prove nothing; other selected observations might be very much at variance with those chosen by Balfour.

Organic gardeners also claim that there are probably many substances present in foods grown according to their methods that are not present in foods grown on chemicals. This is obviously a weak argument, for the reverse is just as likely to be true. As emphasized in other chapters of the present book, chemical fertilizers commonly increase crop yields and crop residues and thus maintain soil humus at approximately the same levels as where animal manures and composts are applied. It follows that any differences in the nutritive values of plants grown under the two systems is likely to be attributable in part, at least, to the supply of inorganic nutrients available to the plants, that may influence the synthetic processes in them. Soils are often deficient in certain major and minor nutrients, even if compost is applied. Knowing this, the manufacturers of chemical fertilizers have usually supplied any such elements that are likely to be deficient. Some of the minor elements may also be supplied separately in highly available chelated forms (Haertl, 1956). Therefore, if a supply of an element, such as Mo, Mn, or Cu is needed for synthesis of a certain organic substance, it is likely that the chemical-fed plant may have an advantage over that fed by nature's methods.

The unknown-substances claim of the organic school has also lost most of its impact in recent years because of the progress made by biochemists. Most of the former unknowns can now either be determined chemically or be tested for by delicate biological methods. Any deficiencies noted can be supplied readily from known sources. The result is that our food supply, grown mostly with chemical fertilizers, is now superior to that in the pre-chemical age. For example, the human scourges beriberi, rickets, infantile scurvy and pellagra that were so prevalent in earlier years are now no longer serious problems in advanced countries. Many other serious afflictions of both man and animals have also been largely eliminated. The sources of the nutrients on which the crops have been grown have not necessarily been the chief factor in these developments; most of the credit must go to the nutrition investigators.

It should also be pointed out that as a result of mass transportation, and chainstore distribution, our food supplies are derived from many regions and many soils, instead of being grown locally as in former years. If one soil is deficient in a minor nutrient, for example, other soils may have an abundance of it. This assures us of an adequate supply of nearly all mineral nutrients.

Hopkins quotes Sir John Russell, former director of the Rothamsted Experimental Station, as follows: "We have searched diligently for evidence that organic manure gives crops of better quality than inorganic fertilizers, and so far our experiments, made jointly with Dunn Nutritional Laboratories at Cambridge, have all given negative results. No differences have been found."

Hopkins (1957) justly emphasizes that even if health had decreased in recent years, we could not attribute this to the use of chemical fertilizers. Many phases of our living conditions and environment have also changed. The situation here is similar to that involving the interrelationship between nutrient sources and the damage produced by disease and insects, discussed earlier in this chapter. There is probably no cause and effect relationship in either case.

The humus school has laid great emphasis on the increasing tendency of populations to eat less fresh food and more processed foods from which vitamins, minerals, and other important nutritive substances have been removed. Usually any low quality in such foods is attributed not to processing alone but also to the use of chemical fertilizers for their production. No-one will argue that the most tasty and possibly wholesome foods are likely to be those taken direct from the garden and eaten while fresh, but this is impractical for most persons who live in cities. But are these city dwellers being supplied with unsatisfactory foods? Certainly not now. Science and industry have remedied any deficiencies that may have existed at one time. The additions to processed food are as readily assimilated as the nutrients in fresh vegetables (Harris, 1959). Even more important is the tremendous progress made in recent years in the frozen food industry. Frozen foods are essentially as nutritious after months of storage as when first harvested.

Hegsted and Stare (1954) point out that about ten amino acids out of a total of 22, a dozen or so vitamins, two or three fatty acids, and at least a dozen inorganic elements are essential in nutrition. All of these can now be supplied in pure form in the amounts needed. Even foods that are naturally deficient in certain nutrients are now enriched to make them better than nature's original product. For example, riboflavin is added to white bread in larger amounts than occur in whole-wheat bread. They state that "there is, of course, no reason to believe that Nature endowed wheat with riboflavin in proportion to the needs of man." Likewise, vitamin D is added to milk to make it more satisfactory for human needs than the original product.

Few foods supply proteins that contain all of the essential amino acids in the ratios that conform to the body's requirements. This is true regardless of how they are grown. The result is an inefficient use of the protein unless supplementary limiting amino acids are supplied, as is now being done. All of the essential amino acids must be supplied at the same time in order to realize maximum efficiency with respect to both growth and health of animals and man. Three of the main foods of mankind – rice, wheat and corn – are deficient in the basic amino acid lysine. This acid is now being used to fortify these grains, thereby greatly increasing their food value.

Stare (1961), a physician and student of nutrition for many years at Harvard and elsewhere, states that "I do not know, nor have I ever heard, of one single case of ill health in man shown to be due to adding *approved* additional chemicals to foods. And I say *additional* chemicals because I wish to emphasize that all foods are chemicals. You and I, too, are chemicals – so much water, protein, fat, carbohydrates, vitamins and minerals." He stresses the desirability of eating a variety of foods to assure a balanced diet and states further that "we have the best and finest food in history – also, the safest. Those of you who've traveled in countries where organic fertilizers are used, and experienced what some of us refer to as 'Bogota belly' or just plain trots, know what I mean. Let those who preach organic gardening visit the Far East, as I have, and really get the feel of it."

Since food processing and handling bears little relationship to the subject of this book, further discussion is definitely out of order. It only needs to be emphasized again that biochemists and nutritionists have made such rapid advancements in recent years that, if a food deficiency were detected in any processed food, the manufacturing process would quickly be modified to produce a satisfactory product.

THE HAUGHLEY EXPERIMENT

When a scientist studies the fantastic claims made by the organic school, he is not impressed because they present no proof. Furthermore, he notes that the organic gardeners often take the attitude that, if anyone doubts their claims, it is up to him to prove that they are wrong. This is really reverse thinking.

According to Balfour, the organic gardeners have repeatedly urged government scientists to set up experiments to test their ideas with regard to health. She admits that long-term, large-scale experiments of the type that she wished are expensive, but infers that more important reasons are "either the chemists are, at heart, not sure of their ground, or else, suspecting that they are wrong, they are fighting to preserve their vested interests at the possible expense of national health. If it had not been for this obstruction, this vital question would surely have been answered long since." The facts are that scientists were obtaining the facts that Balfour sought but not by her methods; they knew of far better ones.

Balfour also states that "broadly speaking then, the mentality of the large scale users of chemical fertilizers is, I think, in the main a commercial mentality; the mentality that measures values in terms of money and is out for quick returns, whereas the 'composters', inevitably made alive all the time to the biological factors of soil, develop different standards. They are very much aware of their responsibility; their outlook is one of service to the soil, not exploitation; farming to them is a vocation, not a trade. When they become convinced that their biological approach to the soil is in the interests of the soil itself, any soil treatment which runs counter to this, becomes such heresy to them that they cease to be capable of a detached and purely scientific attitude to the problems involved." This last statement is indeed surprising.

The desire of the organic school for an experiment that would test their ideas *according to their methods* was finally realized when the Haughley Research Trust was set up in England and preliminary work started in 1940 on a 182-acre area known as the New Bells Farm. Since 1947 the experiment has been under the supervision of the Soil Association.

The New Bells Farm was divided into three sections for the purpose of comparing from the health point of view three systems of farming based on different conceptions of the nature of nutrition. The systems as briefly described by Balfour were as follows: "The first system is based on the ecological conception of nutrition as a cycle – a flow of materials from the soil and back to the soil – in which a vigorous soil population forms an essential sector, being the agency through which humus feeds the plant *indirectly*. The second system is based on the belief that all food materials needed by plants can be provided in the form of soluble chemical nutrients, provided physical conditions are favourable to water retention. The third system is based on the now orthodox view that all farmyard manure, and other humus-forming materials available, should be returned to the soil, but that these must be supplemented by soluble chemical fertilizers because farmyard manure or compost (except in such heavy dressing as to be out of the question practically) are deficient in essential plant food."

The outline of the experiment and the results obtained to date are given in various reports, journals, and news bulletins issued by the Soil Association at New Bells Farm, Haughley, Stowmarket, Suffolk. Obviously, these details are far too extensive to be given here.

No world-shaking results have been obtained to date from these experiments, which is what any trained and experienced agriculturalist would have expected. One cannot compare satisfactorily whole farming systems involving rotations, livestock, cropping, etc., especially on 182 acres. Any answers obtained are, at most, only qualitative, and scarcely that.

Farming involves literally hundreds of factors that vary from year to year and even from day to day. It is difficult enough to make a simple yield test of a single factor, such as one wheat variety against another. Even this requires many replications and years of tests on many soils and under a variety of climatic conditions. The difficulties are greatly multiplied when the main interest is in such an intangible thing as health rather than in yields, as is the case with the Haughley experiment. How could one measure health in such an experiment? Furthermore, how could anyone even compare yields satisfactorily in a livestock farming system without commercial fertilizers with a non-livestock system with commercial fertilizers? The question that immediately arises is: what rate of fertilizer application should be made? By varying the rate of fertilizer added one could arrive at any answer desired, since available nutrient supply is the primary factor that determines yields. In fact, in the systems of farming mentioned neither yields nor health could be compared satisfactorily, for the end products are pounds of beef in one case and pounds of grain in the other.

An examination of some of the results of the Haughley experiment shows comparative yields of potatoes produced on plots fertilized with 6 loads of compost in one case versus 12 loads of farmyard manure on another. Of what scientific or practical value can such data have when neither the moisture nor nutrient contents of the organic additions are given? Apparently no attempt was made to make the nutrient levels the same. Presumably, the organic school considers the organic matter, per se, of far greater importance so far as yields are concerned than the nutrient content of the organic matter sources.

In livestock farming, where all manures and wastes are returned to the soil, and the only product removed is the animals, it is obvious that the maintenance of fertility is a comparatively simple matter. In contrast, in grain farming most of the product is removed as grain and sold on the market. Any direct comparison between the two systems is unfair and may be misleading. The nutrients removed in harvested crops must necessarily be returned in part as fertilizers, if the fertility of the soil on such areas is to be kept at the same level as where livestock is the only marketed product.

Marked changes have been made in agriculture since the Haughley experiment was started that make this experiment far less valuable than the organic gardeners originally expected. Two advances of special importance are: (1) the tendency of farmers to do less cultivating than formerly; and (2) the addition of less animal manure but more commercial fertilizer as a means of maintaining soil organic matter. Among the merits of reduced cultivation, discussed in Chapter 24, are much smaller losses of organic matter by both erosion and biological oxidation. Reduction in the use of animal manures is attributable to fewer livestock on the farm and to the cost of hauling to the field; if applied as compost the costs are much greater. It is easier, and just as satisfactory, to maintain soil humus by adding large amounts of fertilizer to crops that produce abundant quantities of residues that can be returned to the soil. The combination of reduced tillage and abundant nitrogen, therefore, is or can be the answer to the problem of soil organic maintenance. Since organic matter can be maintained without additions of animal manures or compost, and without sacrifice in quality or health, most of the claims of the organic school need no longer be given serious consideration. Chemical fertilizers are a blessing and not a curse. The Haughley experiment will never lead to this conclusion because it is not even designed to test fully and fairly the merits of commercial fertilizers.

WORLD NEEDS FOR FOOD

Great emphasis has been placed in recent years on the world population explosion and the accompanying scarcity of food. In most of the Asiatic countries, and to an only slightly lesser extent in sections of Africa and South America, millions of people are constantly hungry and existing on inadequate diets. In parts of Asia the death rate from starvation is unbelievably high. In short, the world situation is a precarious one and every effort must be exerted to improve it.

The world food situation is well expressed by Dr. Daniel Aldrich Jr. (1965) of the University of California. He states that "if this well-fed continent were called to support its people with the tools of a century ago, we could very well rival some of the world's most underdeveloped nations in poverty and human misery. Of course this is an unlikely sort of 'if'. But there are around us the partisans of a chemical-free world who would have us give up some of the principal tools of modern agriculture.

"The truth is that we have long passed that point where anyone can seriously think of going back to a chemical-free, technology-free agriculture. It is simply a matter of people to feed and clothe.

"Our only hope for meeting the challenge of feeding a hungry world is a food explosion. Fortunately, this is possible. In the Western World we have the technology, equipment, and capital to increase world production of food tenfold in the next 10 years." (In the opinion of the writer this statement is much too optimistic.) "But to accomplish it we will need to rely more than ever on the tools of our technology – fertilizers, pesticides, herbicides, growth regulators, defoliators, and rodenticides. These tools are as indispensable as tractors, hybrid seeds and improved crop varieties.

"What lies ahead, therefore, is a high-density agriculture that will create an even more favorable environment for pests. To cope with this situation we will need more sophisticated, more selective, and more effective chemicals. New lands must be made fit for human life. More foods must be preserved, stored, and moved long distances and this means more and better antispoilage chemicals.

"Amidst this aura of new technology, we must recognize the need to learn still more about all chemicals – the natural ones of our foods and those we formulate by necessity. Whether we like it or not, the world is becoming more crowded. But if we understand the chemistry of all things around us, we can have a more populous world and yet a safer and better nourished one than we have today."

ORGANIC FARMING WITH CHEMICAL FERTILIZERS

Some of the emphasis that the organic school places on soil organic matter is acceptable to agronomists. Most of the pages of this book are devoted to outlining the many benefits to be derived from soil organic matter. It is an extremely important constituent and one of our main problems centers around the question: how do we get enough of it? The only practical means now for getting adequate amounts on large acreages is through the use of chemical fertilizers. There is, therefore, no conflict between those who emphasize the need for soil organic matter and those who champion the use of chemical fertilizers (Hopkins, 1950).

The organic farmers have proposed a philosophy which is in part good for backyard gardeners, and for some areas where commercial fertilizers are not available. However, the adoption in this country of the practices that they advocate would result in inadequate food supplies and a serious lowering of our standard of living. Emil Truog of the University of Wisconsin has been quoted by Butler (1952) as saying that "if all the readily available garbage and organic wastes produced in this country were turned into composts, total production would probably not provide more than 5 to 10 percent of fertilizer elements needed to keep up to satisfactory production."

MacDaniels (1952) in his discussion of organic gardening states that "probably the most disturbing part of the whole organic gardening movement is that it encourages its advocates to go back to the Middle Ages in their thinking about their problems. Mankind has made great progress through the use of the scientific method of solving its problems and in discarding that of the cult and of the mystic philosophy at least insofar as it deals with the natural sciences....... The mystery that is built around the compost pile is making the whole matter unnecessarily complex."

Throckmorton (1951) concluded his discussion of the organic farming myth with the statement that "there is nothing to substantiate the claims of the organic-farming cult. Mineral fertilizers, lime and organic matter all are essential in a sound fertility program. Chemical fertilizers stand between us and hunger."

ADDENDUM

Shortly after completing the writing of this chapter I was surprised to see the article by Grimsrud (1969) that appeared in the December 9 issue of the *Wall Street Journal.* It was entitled "Down-to-earth appeal: organic farming gains a devoted following." Since the article brings out in a very interesting way much new information that I believe will be of interest to the readers of this book, I am (with the consent of Dow Jones and Company) reproducing most of it.

Grimsrud starts his article with the following quote: "In the soft, warm bosom of a decaying compost heap, the wheel of life is turning." The article then continues as follows: "This observation in a pamphlet about organic gardening may seem a bit emotional to the average weekend gardener, who thinks a compost heap is just a smelly pile of manure, rotten leaves and moldy grass clippings. But organic gardeners and farmers take themselves seriously. And because of the current uproar over the safety of pesticides and food additives, a lot of other people now take them seriously, too.

"Organic farmers grow their produce without any help from chemical fertilizers, sprays, dusts or pesticides. There was a time when the market for such foods was a narrow one and the general public probably lumped both the farmers and their customers together with food faddists and eccentric old ladies in tennis shoes.

"No longer. Today more and more ordinary housewives are joining those food faddists at the counter of their neigborhood health food store. Meanwhile, leaders of the organic movement say biologists, doctors, conservationists and others are rallying to their banner.

"There are 1,500 to 2,000 health food stores around the country (not counting the roadside stands some growers operate), and there are plans to launch more. Organic-Ville, a Los Angeles health food supermarket, expects sales to double (to about $1 million) this year, according to its manager. In San Francisco, small groups with names like 'Friends of the Earth' are snapping up organically grown produce at places like 'Far-Fetched Foods', a little store in the Haight-Ashbury district.

"Organic growers raise nearly all the common fruits and vegetables, along with more exotic fare like alfalfa sprouts and the Jerusalem artichoke .....

"Growers also produce organic beef and poultry from animals that eat organically grown food and never get growth-accelerating hormones. Such food is expensive......

"Organic farmers say their food costs more because they have to sacrifice the higher yields chemical fertilizers and pest-killers would give them in order to grow tastier, more nutritious food the way nature intended. Novice farmers often find their ventures far from profitable......

"Insects usually are the biggest problem for organic growers, who devise ingenious means to combat the pests without resorting to chemicals. (These include the use of hogs to eat fallen dates that harbor date beetles; trapping and scalding date beetles; and the use of ladybird beetles to devour aphids)......

"Plant diseases are best prevented by making sure your soil is rich in humus, the decomposed organic matter formed after compost is worked into the soil, organic experts say......

"Organic enthusiasts say they're willing to put up with all kinds of hardships in return for their unpolluted food. Mrs.____, a retired housewife who says her four-and-one-half acre garden near Missoula, Mont., has 'compost piles all over the place,' admits that bugs are a problem. But, she adds, 'I'd rather find a worm in my apple than DDT on it'."

This article speaks for itself and I see no need for further comment.

REFERENCES

Aldrich Jr., D.G., 1965. *Agric. Sci. Rev.*, 3 (1): cover page.

Balfour, E.B., 1950. *The Living Soil.* Faber and Faber, London and Devin-Adair, New York, N.Y., 270 pp.

Bradfield, R., 1954. *J. Agric. Food Chem.*, 2: 1216–1220.

Butler, E., 1952. *Progressive Farmer,* March–June, 1952.

Cazier, M.A., 1953. *J. Agric. Food Chem.*, 1: 1084.

Decker, G.C., 1958. *J. Agric. Food Chem.*, 6: 98–103.

Garrett, S.D., 1960. *Biology of Root-infecting Fungi.* Cambridge Univ. Press, London, 293 pp.

Grimsrud, G., 1969. *Wall St. J.*, Dec. 9: 1.

Haertl, E.J., 1956. *J. Agric. Food Chem.*, 4: 26–32.

Hainsworth, P.H., 1954. *Agriculture – A New Approach.* Faber and Faber, London, 248 pp.

Harley, J.L., 1965. In: K.F. Baker and W.C. Snyder (Editors), *Ecology of Soil-borne Plant Pathogens.* Univ. Calif. Press, Berkeley, Calif., pp. 218–230.

Harris, R.S., 1959. *J. Agric. Food Chem.*, 7: 88–94, 97–102.

Hegsted, D.M. and Stare, F.J., 1954. *J. Agric. Food Chem.*, 2: 960.

Hopkins, D.P., 1950. *Agric. Chem.*, 5: 49–53, 91–93.

Hopkins, D.P., 1957. *Chemicals, Humus, and the Soil.* Faber and Faber, London, 288 pp.

Howard, A. and Wad, Y.D., 1931. *The Waste Products of Agriculture – Their Utilization as Humus.* Oxford University Press, London, 167 pp.

Howard, A., 1940. *An Agricultural Testament.* Oxford Univ. Press, London, 253 pp.
Jacks, G.V., 1959. *Soils Fert.*, 22: 83–84.
Jenks, J., 1959. *The Stuff Man's Made Of.* Faber and Faber, London, 246 pp.
King, F.H., 1911. *Farmers of Forty Centuries.* Democrat Printing Co., Madison, Wisc., 438 pp.
MacDaniels, L.H., 1952. *Bull. N. Am. Gladiolus Counc.*, 29: 61–63.
Murphy, W.J., 1954. *J. Agric. Food Chem.*, 2: 903.
Rayner, M.C. and Neilson-Jones, W., 1944. *Problems in Tree Nutrition.* Faber and Faber, London, 184 pp.
Rodale, J.I., 1946. *Pay Dirt-Farming and Gardening with Composts.* Devin-Adair, New York N.Y., 240 pp.
Stare, F.J., 1961. *Farm J.*, February: 42.
Throckmorton, R.I., 1951. *Country Gentleman,* September, 1951.
Wadleigh, C.H., 1965. *J. Soil Water Conserv.*, 20: 43–45.

ORGANIC SOILS

Chapter 29

FORMATION AND CHARACTERISTICS OF PEATS AND MUCKS

DEFINITIONS

Organic soils, or the deposits from which organic soils are derived, have been designated by many names (Waksman, 1942; Dawson, 1956) but are usually called peats or mucks. Each of these terms has been modified by the use of many special terms based on the plant source of the material, location, land elevation, moisture conditions where formed, pH, amount of salt in the water where formed, mode of origin, inorganic matter content, etc. In addition, there are many synonyms in common use, such as turf, humus, moss and mull.

Waksman (1942) has defined peat as "a layer of the earth's crust, largely organic in nature, which has originated in water basins and in a water-saturated condition as a result of incomplete decomposition of the plant constituents due to the prevailing anaerobic conditions. The nature of the peat depends upon the plant association which has given rise to it, and which in turn has been controlled by the nature and amount of the mineral nutrients in the waters in which the plants were growing. The chemical composition of peat is influenced by the nature of the plants from which it has originated and by the moisture relations during and following its formation and accumulation." Peat always contains considerable mineral matter, but usually less than 35% (Anderson et al., 1951) on the dry weight basis.

Muck is a term that is usually applied to organic soils that contain more than 35% (dry weight) of inorganic material, and in which the botanical origin of the organic matter can no longer be readily identified. In practice, a muck soil is usually a peat deposit that has been drained and cultivated, and in which the surface layer has undergone considerable oxidation and disintegration of the original peat fibers.

The use of the terms, peat and muck, vary markedly from region to region and, obviously, there can be no clearly-defined line of demarcation between them. Suffice it to say that peats tend to be rather coarse, fibrous, materials; mucks tend to be fine-grained, more colloidal, more decomposed, and behave more like inorganic soils because of particle size and higher percentage of mineral matter, particularly clays.

Kinds of peats

Organic soils are found widely distributed all over the world where the climatic conditions have favored heavy growths of vegetation that decomposed slowly under water, and where anaerobic conditions have prevailed for centuries. Table 29.I, taken from Burke

TABLE 29.1

ORGANIC SOILS OF THE WORLD (from BURKE and O'HARE, 1962)

Country	*Area (1,000 acres)**	*Country*	*Area (1,000 acres)**
Austria	100	Ireland	3,000
British Guiana	30	Israel	15
Canada	278,000	Italy	250
Czechoslovakia	30	Malaya	1,000
Denmark	350	New Zealand	400
England and Wales	4,000	Norway	7,400
Finland	20,000	Poland	5,000
France	250	U.S.A.	25,000–30,000
Germany (all Germany)	6,000	(Alaska)	110,000
Holland	200	U.S.S.R.	175,000
Hungary	200	Scotland	2,000
Iceland	700	Sweden	15,000

*1,000 acres = 400 hectares (approx.).

and O'Hare (1962), shows the vast extent of organic soils in the world. A considerable portion of these areas consists of undeveloped peatland.

According to Broadbent (1960), pollen analysis and radiocarbon dating indicate that the rate of accumulation of organic soils is about one foot in 500 years. This value would vary widely from place to place with climatic conditions. It is not unusual for peat beds to experience cycles of gains and losses as climatic conditions change.

Radiocarbon measurements on two peat profiles near Belle Glade, Florida, made by McDowell et al. (1969), indicate that peat formation began about 4,400 years ago. During the first 500–1,000 years about 7.6 cm of basal mucky peat, consisting of a mixture of marl and organic matter, was built up. Subsequently, plant growth increased rapidly as a result of environmental changes and a rise in sea level. By 1914 A. D. the peat had developed to a depth of about 3.65 m, or an average of about 8.4 cm per century during the entire period of peat formation. During the last 50 or so years since drainage operations were initiated, about a half of the peat profile has disappeared.

The peat and muck acreage in the United States, exclusive of Alaska, has been estimated by the Soil Survey Division of the U.S.D.A. (1938) to be about 79 million acres, a value considerably greater than that shown in Table 29.I. The quantity of air-dry peat in the United States, exclusive of Alaska, has been estimated by the U. S. Geological Survey as nearly 14 billion tons. Nearly 50% of this is in Minnesota; Wisconsin, Florida, and Michigan follow in decreasing order (Feustel, 1938). Extensive areas of peat are also found on the Pacific Coast and in widely scattered sections of the more humid regions of the United States.

Rigg and Gessel (1956) give a description of the peat deposits in the State of Washington that emphasizes the various kinds of plants involved, and the differences in physical and chemical properties. They examined 325 deposits that varied in depth from 3 to 63 ft. They found that "the kinds of peat in the order in which they commonly occur from top to bottom and the plants from whose remains they were formed are *(1)* moss peat from various species of *Sphagnum*, *(2)* fibrous peat mostly from sedges, *(3)* woody peat from logs, twigs and leaves, and *(4)* sedimentary peat from microscopic plants. Moss peat is absent in many deposits." The associated mineral materials consisted of marl, diatomaceous earth, and volcanic ash.

Peats have been classified according to various systems, none of which are very satisfactory. This is because they are formed from many plant species under a variety of climatic conditions that change from time to time. Waksman (1942) lists four predominant types of peats. These are: *(1)* highmoor or upland peat; *(2)* lowmoor or lowland peat; *(3)* forest peat; and *(4)* aquatic peat. These differ rather markedly in origin and final characteristics.

Highmoor or upland peat

This is primarily a sphagnum moss peat formed chiefly in colder regions of high rainfall, particularly in northern Europe, Canada and in the northeast and northwest portions of the United States. The various species of mosses involved may grow directly on soil or rocks if the rainfall is high, or if there is drainage of water from higher levels. Sometimes the mosses may also grow on top of lowmoor or forest peats. According to Waksman, *Calluna, Pinus, Cassandra, Ledum, Andromeda, Eriophorum, Rynchospora* and *Scheuchzeria* are commonly found. Ferns, sedges and orchids are less common. This peat is a loose and spongy type and commonly very acid, since it is formed in waters that are low in mineral elements, especially calcium.

Lowmoor or lowland peat

The predominant plants involved in the formation of this type of peat are various sedges, reeds, shrubs, grasses and trees. These plants grow chiefly in shallow lakes or bogs, and in river valleys. The lakes and bogs are gradually filled up and as this occurs there may be a gradual change in the predominant flora. Sedges, reeds and grasses are likely to give way to shrubs and trees. Lowmoor peats, the predominant type in the United States, are commonly only slightly acid, and are sometimes alkaline, depending on the source of the water in which the plants grow, and on the nature of the soil or rocks upon which the peat is formed.

Forest peat

A large number of types of trees and shrubs are involved in the formation of forest or swamp peat. These include pine, spruce, oak, alder, birch, juniper, maple, elm, larch, willow, heather, cranberry, *Andromeda*, sedges and many other species. These woody peats are formed along rivers and in bogs where the rainfall is high, or where there is an abundant supply of drainage water. They consist of the residues of the tree trunks, limbs, branches, bark, etc., together with the remains of other plant materials, often in an only partially-decomposed condition. These peats are acid, but not to the extent that most sphagnum peats are.

Aquatic peat

This is not a commonly-encountered type, since it is a sedimentary peat usually formed as the bottom layer of a bog peat. It is derived from aquatic plants, chiefly algae, and from pollen and spores. Much clay may also be present. When sufficient of this type of material has accumulated it is common for reeds, sedges, grasses and shrubs to become rooted in it, or on the banks of the bogs, where eventually a considerably different type of peat begins to form. This new growth gradually suppresses the growth of the original aquatic plants. Aquatic peat is largely colloidal in nature, and usually only mildly acid.

More extensive descriptions of the various types of peat and the kinds of vegetation involved are given by Dachnowski (1919), Waksman (1942), and Davis (1946).

PROFILE OF A PEAT BOG

The essential requirements for the formation of a peat deposit several feet thick are: such conditions that a mass of plant growth can form continuously over a period of centuries; and that the dead plants or plant parts can accumulate in a largely undecomposed form. This is what happens in a bog or shallow lake where water is present for most of the time. Under such conditions the oxygen content of the water at the bottom is usually very deficient because of slow solution, and because respiration of microorganisms and higher plants removes it about as fast as it diffuses downward from the surface. In the absence of adequate oxygen, decay is largely limited to the initial stages of the process. The conditions here are not unlike those existing where wooden piles are driven into a lake bottom. Such piles may remain for decades in perfect condition at the bottom of the lake and in the soil, but undergo comparatively rapid decay at the water surface.

The retardation of decomposition of plant materials in a peat bog may also be aided in some instances by the formation of toxic materials. According to Robinson (1930) these may include ferrous iron and manganese. The chief gases evolved are carbon dioxide, methane, hydrogen, and hydrogen sulfide, but these probably have little effect on the anaerobic population; if not used by the microorganisms present in the bog water they readily escape to the atmosphere.

The profile of a peat deposit commonly shows very clearly the successions of plant life that occurred during the period of perhaps 2,000–10,000 years required for it to form. The first organic additions, found at the bottom of the deposit, are largely material of foreign origin, such as pollen, spores, and other plant materials. Mixed with these transported materials are the remains of plants, especially algae and other plankton, and inorganic materials transported by winds or water.

Above this sedimentary layer are likely to be the sedge and reed remains, but sometimes forest residues rest directly on the sedimentary layer. The types of plant successions, and predominant species, vary widely with climate, geology, and topography. Over the long period required to form a thick bed of peat there are usually wide variations in climate. A long period of abundant plant growth may be followed by a period of low rainfall and a consequent lowering of lake level. When this occurs, oxidation of the old plant remains may proceed at a rapid rate for a time. In addition, trees may gain a foothold if the dry period lasts long enough, replacing sedges, reeds and grasses. The reverse may also occur. These climatic cycles, with their corresponding plant cycles, account in large part for the variability of peat, even from a single deposit. Fig. 29.1, drawn by Dachnowski-Stokes (1933), illustrates typical stages in the process of peat formation.

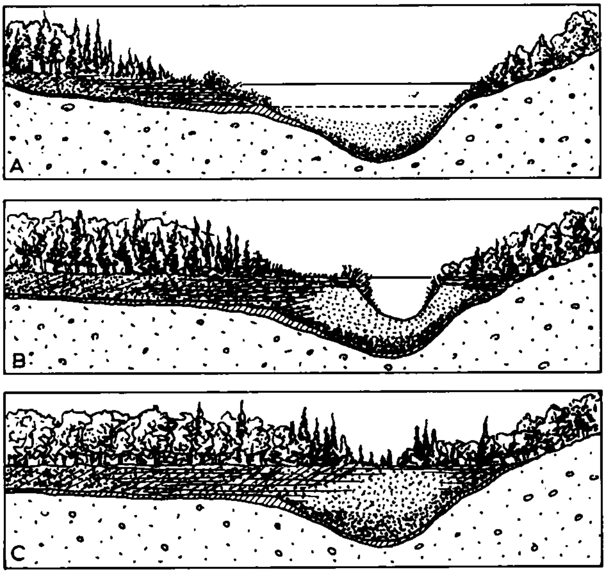

Fig. 29.1. Graphic presentation of stages of vegetation in the formation of a peat deposit over a depression that contained an older body of standing water. It illustrates the formation of *A*, sedimentary; *B*, fibrous; and *C*, woody peat. (From Dachnowski-Stokes, 1933.)

A layer of sphagnum peat may form on top of the other types of peat after the bog has been completely filled, if the climate is sufficiently cool and the rainfall adequate to keep the sphagnum mosses in a continually moist condition. Doubtless one of the chief reasons that the mosses are transformed into peat under these conditions, rather than being decomposed completely into carbon dioxide and water, is that moss tissues are very resistant to decay. The low temperatures, low evapotranspiration, and low pH characteristic of regions where sphagnum peats form, are also major factors. The oxygen partial pressure in masses of sphagnum residues is probably less than in the air, but the conditions are unlikely to be sufficiently anaerobic to account for the organic accumulations. This is emphasized by the fact that sphagnum mosses commonly grow in climates such as that of New Jersey, but moss peats do not occur there to any appreciable extent.

THE ROLE OF MICROORGANISMS IN PEAT FORMATION

Microorganisms are major factors in peat formation, although the magnitude of the biochemical changes that they bring about may seem small during any ordinary period of observation. The accumulative effect of these changes over a period of several centuries is, however, large.

The initial step in peat formation differs little from that which occurs when plant materials are decomposed in soil, or in a compost pile. The readily decomposable sugars, fats, starches, etc., are oxidized chiefly by aerobic organisms. Some of the protein may also be attacked, but this depends on the percentage present. Usually the protein either remains tied up in the plant material or, if any of the nitrogen is liberated, it is used immediately by the microorganisms and higher plants present. Any ammonia liberated and not so used would tend to remain as such, since nitrifying organisms are absent or few in number. Most of these initial changes occur before the plant residues and dead plants have dropped to the bottom of the lake or bog and become an intimate part of the layer that will later be transformed into peat. The cellulose, lignin and hemicellulose remain largely unattacked in these initial stages of decomposition.

In the second stage of peat formation the plant residues are very slowly decomposed, largely by anaerobic bacteria. Undoubtedly some chemical reactions occur, but the main changes are those brought about enzymatically by the anaerobes. Waksman (1942) has shown that in a peat bog the numbers of fungi and actinomyces decrease with depth, whereas the anaerobic bacteria tend to increase somewhat. Present evidence indicates that these anaerobes are chiefly responsible for the conversion of much of the cellulose into methane and hydrogen, but cellulose destruction may be markedly curtailed if the pH drops too low. In sphagnum peat formation, cellulose decomposition proceeds more slowly and less completely than in reed and sedge peats, both because of the higher acidity and also because it is more resistant to biological attack, presumably because of the interrelations of the cellulose–lignin–protein structures. Lignin, which undergoes little decomposition, characteristically protects other plant constituents from attack.

PROPERTIES OF PEATS

Mineral constituents

The total mineral content of peats is dependent primarily upon the extent to which the residues of the peat-forming plants are diluted with sand, silt, clay and calcium carbonate transported from surrounding areas. Where no such washed-in or wind-blown materials are present the minerals are largely limited to those originally assimilated by the plants from the soil or waters where they grew.

The chemical composition of the ash of several representative types of peat as reported by Feustel and Byers (1930) is given in Table 29.II. In column 4 of this table is given the

TABLE 29.II

CHEMICAL COMPOSITION OF ASH IN SEVERAL TYPES OF PEAT (from FEUSTEL and BYERS, 1930)

Type of peat	*Location State*	*Depth (inches)*	*Ash in dry peat (%)*	*Inorganic constituents of the ash (%)*												
				soluble SiO_2	*insoluble SiO_2*	*Fe_2O_3*	*Al_2O_3*	*TiO_2*	*P_2O_5*	*CaO*	*MgO*	*SO_3*	*CO_2*	*Na_2O*	*K_2O*	*MnO*
Sphagnum	Maine	8–12	2.29	7.78	24.03	4.15	11.58	0.42	4.53	24.31	9.86	5.94	4.87	1.02	1.35	0.13
Sphagnum	Maine	8–12	1.55	–	29.29*	5.56	11.16	0.53	7.76	12.68	20.68	8.13	1.11	0.91	1.73	0.06
Heath	N. Carolina	3–9	2.33	12.12	34.00	4.56	9.96	0.58	3.10	10.20	13.50	8.80	0.75	1.30	1.30	0.01
Sedimentary	N. Carolina	24–30	6.74	5.36	66.46	2.16	10.01	1.15	0.50	6.30	4.10	4.70	–	0.50	0.30	tr.
White cedar forest	N. Carolina	36–42	27.05	4.34	73.02	3.20	13.96	1.34	0.50	1.30	0.70	1.00	0.44	0.30	0.60	0.01
Saw-grass	Florida	4–6	6.67	4.80	4.31	2.10	0.81	0.39	1.50	44.15	7.30	7.60	25.84	0.32	0.44	0.07
Saw-grass	Florida	94–96	17.82	17.44	27.06	3.20	8.10	1.70	0.35	21.75	5.85	4.30	9.44	0.42	0.48	–
Sedimentary	Florida	42–48	10.27	15.58	20.19	7.25	7.39	0.71	1.65	22.40	5.85	11.55	6.08	0.56	0.36	0.02
Woody sedge	Washington	0–6	10.84	10.28	24.00	28.20	11.40	0.45	3.95	11.90	2.33	4.47	1.20	–	0.86	0.80
Herbaceous sedge	Washington	10–16	6.51	8.04	9.65	24.90	15.33	0.50	3.83	21.85	1.99	7.60	4.37	0.83	0.43	0.80

*Total SiO_2.

ash content on a water-free basis of the various samples of peats. It will be noted that there is little relationship between the total mineral content of the peats and the percentage of the various mineral elements in the peats. The kinds of plants from which the peats were formed and the places where they grew seem to be the controlling factors in the determination of the percentages of each of the eleven mineral elements listed. Sphagnum peats tend to be low in ash, whereas reed and sedge peats and often forest and sedimentary peats have high ash contents. Reed and sedge plants commonly show luxury consumption of minerals which is due in part to the high content of inorganic elements in bog waters.

The contents of phosphorus and potassium shown in Table 29.II, and in Table 29.III taken from Dachnowski-Stokes (1933), are very low, as would be expected. These mineral nutrients are inadequate to support a good growth of most plants. The contents of calcium and magnesium are variable. The nitrogen content varies over the range of about 0.8 to 3.1%. The lower percentages are characteristic of acid sphagnum peats, and many of the coniferous peats. The sedge and reed peats, and many of the sedimentary peats, have the highest percentages of nitrogen. This nitrogen is present in organic compounds and unavailable for crop use until considerable decomposition by microorganisms takes place. When this occurs the nitrogen content of the residual material tends to increase as the carbon is released as carbon dioxide.

TABLE 29.III

FERTILIZER CONSTITUENTS OF VARIOUS KINDS OF MOISTURE-FREE PEATS (from DACHNOWSKI-STOKES, 1933)

Type of peat and condition	*Total nitrogen N (%)*	*Phosphorus P_2O_5 (%)*	*Potassium K_2O (%)*	*Calcium Ca (%)*	*pH*
Moss peat:					
Poorly decomposed	0.79	0.05	0.06	0.12	–
Poorly decomposed	0.75	0.10	0.03	0.47	3.8
Partly decomposed	0.87	0.02	0.02	0.23	3.6
Largely decomposed	1.35	0.05	0.05	1.78	–
Reed peat:					
Poorly decomposed	2.29	0.16	0.05	3.02	–
Largely decomposed	3.07	0.17	0.03	4.99	–
Sedge peat:					
Poorly decomposed	1.63	0.07	0.04	0.50	–
Partly decomposed	2.10	0.05	0.04	1.52	–
Partly decomposed	2.34	0.06	0.09	3.87	7.1
Woody sedge peat	3.14	0.42	0.09	1.29	4.6
Woody peat:					
Coniferous	0.82	0.14	0.16	0.35	3.7
Deciduous	1.73	–	–	–	–
Sedimentary peat:					
Colloidal	0.74	0.03	0.02	0.42	3.5
Colloidal	2.12	0.19	0.31	2.59	6.2
Colloidal	2.71	0.23	0.005	8.41	6.8

TABLE 29.IV

CHEMICAL COMPOSITION OF THE ORGANIC MATTER OF VARIOUS PEATS (from FEUSTEL and BYERS, 1930)

Type of peat	*Location*	*Depth (inches)*	*Ash in dry peat (%)*	*Ether soluble (%)*	*Alcohol soluble (%)*	*Water soluble (%)*	*Hemi-cellulose (%)*	*Cellu-lose (%)*	*Lignin (%)*	*Total C (%)*	*Total N (%)*	*C/N*
Sphagnum	Orono, Me.	8–12	2.29	2.83	4.95	5.62	24.1	17.1	18.01	52.23	0.88	59.4
Sphagnum	Cherryfield, Me.	8–12	1.55	2.39	5.25	5.82	21.3	12.7	22.41	52.76	0.82	64.3
Heath	Beaufort, N.C.	3–9	2.33	2.11	7.02	3.38	8.0	4.9	55.67	59.20	1.71	34.6
Sedimentary	Beaufort, N.C.	24–30	6.74	9.36	7.08	1.48	0.7	1.7	65.90	65.70	0.79	83.2
White cedar forest	Beaufort, N.C.	36–42	27.05	2.29	6.80	5.10	1.1	0.6	33.87	55.07	1.12	49.2
Saw-grass	Belle Glade, Fla.	4–6	6.67	0.45	2.04	3.56	10.9	4.0	48.50	58.48	3.75	15.6
Saw-grass	Belle Glade, Fla.	94–96	17.82	0.75	1.98	2.06	3.8	2.8	59.25	60.12	2.85	21.1
Sedimentary	Miami Canal Lock, Fla.	42–48	10.27	0.47	1.71	2.86	4.2	1.7	46.11	53.21	3.93	13.5
Woody sedge	Monroe, Wash.	0–6	10.84	1.82	7.43	8.89	8.1	2.7	35.64	56.42	3.52	16.0
Herbaceous sedge	Monroe, Wash.	10–16	6.51	2.01	5.67	5.94	7.0	3.2	38.16	56.60	3.75	15.1

Organic constituents

The organic constituents in peats are known only in a general way. Table 29.IV from Feustel and Byers (1930) gives a typical analysis of several representative types of peat. The chief constituent is lignin with varying amounts of cellulose, hemicellulose, and nitrogen constituents that are commonly grouped as protein. How much of this nitrogen is actually present as protein is not known with accuracy, but it is probably less than 30%. This is discussed by Waksman (1942). Peat is generally devoid of starches, fats and sugars. They are eliminated from dead plant materials in the initial aerobic stages of peat formation. The remaining constituents are cellular and fibrous tissues that are low in nitrogen. Some waxes, resins and other complex compounds may be present in small amounts.

The composition of nine natural plant materials that give rise to peat was reported by Waksman and Stevens (1928a,b) and Waksman (1942). These showed average lignin, cellulose, hemicellulose and protein contents of 24.7, 21.6, 21.1 and 5.6%, respectively. The corresponding average values for the organic matter in the ten peats listed in Table 29.IV are: 47.1, 5.4, 9.4 and 16.1%. These data, although not directly comparable, do emphasize that during the process of peat formation lignin and nitrogen tend to remain, whereas cellulose and hemicellulose undergo a decided decrease. The outstanding exception to this general trend is the sphagnum peats from Maine. These show comparatively little decrease in cellulose and hemicellulose, and only a moderate increase in lignin and nitrogen, when compared with the original composition of undecomposed sphagnum.

Water relations

The most characteristic property of peat, when considered from the standpoint of its use in agriculture, is its ability to absorb water. Feustel and Byers (1930, 1936) found, as shown in Table 29.V, that sphagnum peats may absorb 1,000–3,200% of water; the corresponding values for saw-grass and sedge peats are 300–1,500%, and for sedimentary and woody peats 300–700%. This emphasizes the extent to which all peats, but especially those derived from sphagnum, act as sponges in absorbing water.

Air-drying of peats usually markedly reduces the readiness with which water is absorbed and also the total amount that is taken up. The data in Table 29.V show that this is true whether moisture content is expressed in terms of maximum moisture-holding capacity or as moisture equivalent (moisture held against 1000 times the force of gravity). Often prolonged soaking is necessary to bring about thorough wetting, and even then the moisture taken up may be only 25–60% of that held by peat in its natural condition. When drying occurs, the colloidal nature of the natural peat is changed and, like other colloids, rewetting does not restore the original colloidal condition. Furthermore, on drying much of the water absorbed in and on the peat particles is replaced by air. Only a wetting agent, such as alcohol, or greatly-reduced air pressure, brings about a ready removal of this absorbed air.

TABLE 29.V

MOISTURE-HOLDING CAPACITIES AND SPECIFIC GRAVITIES OF SEVERAL TYPES OF PEAT (from FEUSTEL and BYERS, 1930)

Type of peat	*Location*	*Depth (inches)*	*Ash in dry peat (%)*	*Volume wt. (g)**	*Maximum moisture-holding capacity (%)*		*Moisture equivalent (%)*		*Air-dry moisture (%)*	*Apparent specific gravity*		*Absolute specific gravity (oven-dry)*	*Maximum shrinkage (%)*
					natural moisture	*after air-drying*	*natural moisture*	*after air-drying*		*saturated*	*oven-dry*		
Sphagnum	Orono, Me.	9–12	2.29	0.42	2,420	1,485	558	501	11.2	1.016	0.14	1.557	71
Sphagnum	Orono, Me.	36–48	–	0.59	2,735	1,585	572	481	–	–	0.08	1.525	–
Woody	Orono, Me.	120–132	–	0.77	1,070	278	447	206	–	–	0.78	1.463	–
Sphagnum	Cherryfield, Me.	8–12	1.55	1.08	1,690	858	422	343	9.0	1.017	–	1.473	–
Heath	Beaufort, N.C.	3–9	2.33	0.87	772	269	357	142	8.4	1.047	0.55	1.433	78
Sedimentary	Beaufort, N.C.	24–30	6.74	1.05	348	157	211	112	5.9	1.083	0.56	1.105	57
White cedar forest	Beaufort, N.C.	36–42	27.05	1.16	643	162	346	101	7.8	1.074	0.90	1.557	83
Saw-grass	Belle Glade, Fla.	4–6	6.67	0.59	1,280	515	449	250	13.8	1.186	0.45	1.563	81
Saw-grass	Belle Glade, Fla.	94–96	17.82	1.03	1,485	392	501	204	13.4	1.024	0.51	1.490	87
Sedimentary	Miami Canal Lock, Fla.	42–48	10.27	1.03	616	414	303	204	14.1	1.048	0.68	1.551	78
Woody sedge	Monroe, Wash.	0–6	10.84	1.11	300	299	108	111	10.3	1.105	–	1.513	–
Herbaceous sedge	Monroe, Wash.	10–16	6.51	1.03	1,024	577	414	228	10.2	1.031	–	1.469	–

*The weight of a cubic centimeter of peat in the natural condition.

Marked shrinkage in the volume of a peat mass during drying is characteristic of all peats, although the extent of shrinkage varies considerably. Data for seven peats in Table 29.V show shrinkage values over the range of 57–87%. Expressed in reverse, the shrinkage was to 13–43% of the original volumes. Davis (1946) gives similar data for several Florida peats. The final volumes in percentage of the original volumes of the peats were: saw-grass 20–25%; semi-aquatic 10–15%; woody 30–35%; lake bottom sedimentary 10%; fibrous mangrove 40–50%; and a strongly fibrous sample 45–60%. He states that, in general, sedimentary plastic peats shrink most and the moss fibrous and matted sedge peats shrink least.

The water storage characteristics of several Minnesota peats in situ, as determined by Boelter (1964), were shown to vary markedly with peat type. Surface horizons of sphagnum moss peat had large pores and released about 80% of the water by volume at low suction (0.1 bar). In contrast, decomposed and herbaceous peats from horizons below 25 cm had small pores, although high porosity, and were not easily drained. They released only 25–35% water by volume under the same suction. These data emphasize that water table fluctuations in a peat profile do not in themselves indicate the quantity of water involved. Furthermore, peat types must be considered in drainage operations.

Boelter (1966) gives a good discussion of the hydrologic characteristics of organic soils. He states that the suggestion has been made that peat deposits are excellent aquifers that store excess snowmelt water in the spring and gradually release it during the summer, thereby maintaining streamflow. However, this idea is largely erroneous; these watersheds play a more conservative role. Although organic soils have high water contents (Table 29.VI) the decomposed (aggregated) and herbaceous peats have very low specific yields and hydraulic conductivities, and are poor aquifers (Table 29.VII). The usable storage capacity of a bog is in the horizons of undecomposed peats. Water flows comparatively rapidly from such peats, but once the surface horizons are drained, the lower dense horizons would likely provide too little water too slowly to maintain streamflow. Peats that have intermediate properties would doubtless supply water for somewhat longer periods.

TABLE 29.VI

WATER CONTENTS OF SEVERAL ORGANIC SOILS AND A MINERAL SOIL (from BOELTER, 1966)

Material	*Water content (% of volume)*	*Bulk density (sat. vol. basis, g/cc)*	*Water content (% oven-dry weight)*
Peat:			
Sphagnum	40	0.02	2,000
Aggregated	40	0.24	167
Herbaceous	40	0.16	250
Mineral soil:			
Barnes loam	40	1.29	31

TABLE 29.VII

HYDROLOGIC CHARACTERISTICS OF SEVERAL PEAT AND MINERAL SOIL AQUIFERS (from BOELTER, 1966)

Material	*Total porosity (%)*	*Specific yield (gall./cu. ft.)*	*Rate of water movement* (ft./day)*	*Aquifer class*
Peat aquifer:				
Moss peat (surface horizons)	95–100	5.91	118.74	Good
Moss peat (deeper horizons)	81–85	2.47	4.48	Good
Woody peat	87–90	1.87	12.16	Good
Decomposed peat	81–85	0.75	0.016	Poor
Herbaceous peat	85–92	1.12	0.021	Poor
Mineral soil aquifer:				
Clean gravel	30–40	1.87	2403.33	Good
Medium sands	35–40	1.50	500.67	Good
Glacial till	40–50	0.37	0.05	Poor

*Rates of water movement are calculated on the basis of a 100% hydraulic gradient.

Specific gravity and volume weight

Apparent specific gravity values also emphasize the importance of water in determining characteristics and use of various peats. The apparent specific gravity of the saturated peats, listed in Table 29.V, falls within the range of 1.016–1.186, being lowest of course for those that retain the largest amounts of moisture. Apparent specific gravities determined on oven-dried peats fall in the range of 0.08–0.90, being generally highest where the largest amount of inorganic material is present and where the water-absorbing power is lowest; comparable values for mineral soils are usually near 1.1–1.2 for clays and 1.6–1.8 for sands.

The absolute specific gravities (Table 29.V) of the oven-dried peats range between 1.105 and 1.563, with an average value of 1.475. With the exception of the one sample of sedimentary peat from North Carolina, all values lie between 1.433 and 1.563. The corresponding absolute specific gravity values for mineral soils of average humus content commonly fall between 2.6 and 2.8.

Volume weight, which is a term used frequently to characterize a peat, refers to the weight of a unit volume of peat as it occurs under natural conditions. If the weight of a similar volume of water is taken as 1.0, it will be observed from the data in Table 29.V that the volume weights of peats are usually less than unity. They are lowest for those peats that have a high water-absorptive capacity and occur in the upper part of the profile. Values near or slightly above 1.0 are common for peats that contain more ash, and are derived from the lower parts of the profile.

Absorption and buffer capacity

Most peats have comparatively high absorptive, exchange and buffering capacities. The exchange and buffering properties are greatest for the more decomposed types of peat, and are attributable chiefly to the high colloidal content. These colloids are similar to or identical with colloidal organic matter of mineral soils, discussed in an earlier chapter. These properties, together with the ability to absorb water, account for most of the benefits realized when peat is used in potting mixtures in the greenhouse.

In studies with insoluble peat humic acids, Szalay and Szilágyi (1968) found that these organic substances retained Cu, Zn, Mn and Mo so tenaciously that the "symptoms of deficiency of these nutrients in plants growing on drained moor, or peatland soils, could well be caused by such retention." In addition, Co was also so strongly held that plants grown on such soils supplied inadequate amounts to meet the needs of animals fed on the plant material.

PRINCIPAL BOG SOILS OF THE UNITED STATES

The Soil Survey Division of the U.S.D.A. (1938) has described the principal peat and muck soils of the United States as they occur in different geographic regions and under different local conditions. This information is presented here essentially as originally published, except for some condensation and omission of portions that are either not considered very essential or are adequately covered elsewhere in the present publication. The original discussion deals with four areas, and also with coastal marshland peats that occur in scattered areas near the ocean.

The authors point out that organic, or bog, soils present many land-use problems such as those connected with market gardening, farming, wildlife preservation, water conservation, control of floods and erosion, and use as sources of organic matter for soil improvement. The character of the surface material, profile, mineral substratum, and groundwater conditions determine the suitability of the soils for special crops such as onions and celery, or for grain and livestock farming.

Northern areas

(1) Geographic setting and climate. Northern areas of peat and muck are located in a cool-temperate, humid region extending from northeastern Maine and northwestern New Jersey to Minnesota and Illinois, and in other areas of somewhat similar climate in northern Idaho, northern valleys, and along borders of lakes.

(2) Native vegetation. Swamp forests of spruce, tamarack, and arborvitae occur in the north, and various conifers, maple, elm, and ash farther south; reed and sedge are found in marshes; and sphagnum moss and heath are present in bogs.

(3) Soils. In Maine raised bogs are common. A typical profile consists of three main

layers. The upper layer is a yellowish-brown, poorly-decomposed, strongly acid, spongy-fibrous moss peat, about 4–6 ft. thick. Under this is a dark-brown layer of acid woody peat 1 or 2 ft. thick, containing logs, stumps, litter, and woody fragments from conifers. The bottom layer is a brown fibrous peat derived from thin roots and underground stems of sedges and grasses common to marshes. It is 3–4 ft. thick and moderately acid. These three layers rest on plastic organic sediments that accumulated from aquatic plants growing in shallow water over sand, clay, or bedrock.

Farther south the residue of reeds, sedges, conifers, maple, ash, and elm are abundant on the surface. Better drainage conditions and higher temperatures result in the formation of well-decomposed, mellow friable muck that is neutral or only slightly acid. Rifle peat and Carlisle muck are representative of this type of peat.

(4) Use. Since the peats located in the north are less decomposed than those in the south they are not especially favorable for crops, and are subject to late and early frosts. Pasture grasses, hay and, in places, corn and potatoes can be grown on woody and fibrous sedge peat if well drained, and if there is little danger of frost. Most timbered areas can best serve as wildlife refuges and for timber production. Some moss peat may be used for stable bedding, poultry litter, or as sources of soil organic matter.

Types of dark-brown or black granular muck have produced large quantities of vegetable crops and are often used for grain production and stock farming. Fertilizers, especially potash, can be used profitably. Rotations with oats and rye are common when the principal crops, such as onions, celery, and cabbage are threatened with insects and plant diseases. The production of reed and sedge peat and muck for soil improvement is of commercial importance in this area.

Southeastern Coastal Plain areas

(1) Geographic setting and climate. Extensive areas of woody and fibrous peat and muck occur in the flat seaward part of the southeastern Atlantic Coastal Plain. They are found on level upland terraces and border most lakes, ponds, and streams near sea level. An abundance of rainfall and a relatively high temperature favor decomposition and a leaching out of bases.

(2) Native vegetation. Swamp forests of cypress-tupelo-gum, and canebrakes, predominate.

(3) Soils. The peat is usually woody, dark brown, moderately well decomposed, and strongly acid. It contains buried logs and stumps, and has been built up on level sandy plains from a succession of two or three different forests dominated by cypress or white cedar and by mixtures with gum and red maple.

The most common types of the fibrous peats are derived from underground stems and roots of dense stands of cane, sedges, rushes, and grasses accumulated in water basins or on land with a rising water table. There are also large areas of woody-fibrous peat that developed from a mixed open growth of canes and sedges interspersed with bay shrubs, gallberry, and myrtle. The content of plastic colloidal material is often comparatively high, and appears to be a factor in retarding the growth of crops.

(4) Use. There is little agricultural development in this peat area, typified by the Dismal Swamp of Virginia and Okefenokee Swamp in Georgia. These areas can best serve as parks, wildlife reservations or for timber production.

Everglades and related areas

(1) Geographic setting and climate. The Everglades of Florida is the largest peat area in the Gulf Coastal Plain, but there are many similar smaller marshes. Some of these are filled water basins; some border lakes, ponds and wooded streams; and others are accumulations built up on sandy plains or, as in the case of the Everglades, on bedrock near sea level. The rainfall is heavy and the climate subtropical and humid.

(2) Native vegetation. The marshes support a luxuriant growth of sedges, grasses and rushes. The swamp forests contain cypress, tupelo and various other trees and shrubs.

(3) Soils. Black muck, developed from organic sediments from aquatic vegetation, occurs within a narrow belt bordering the southern shore of Lake Okeechobee. It contains some silt and clay and is dense and sticky when wet; when dried it shrinks, cracks and crumbles into a granular mass. Most of this muck is underlain by brown, fibrous sedge peat resting on bedrock.

Brown or dark-brown partly-decomposed fibrous sedge peat occupies most of the Everglades. It consists chiefly of fine roots and coarse underground stems of sawgrass. In the outer border of the area there occurs fibrous, porous material, but in the interior of the Everglades a black, pasty sedimentary layer occurs below the surface, which is relatively impervious to plant roots, air, and water. It is underlain by brown or dark-brown fibrous sedge peat that rests on limestone.

(4) Use. The Okeechobee muck is used chiefly for the production of sugar cane and various vegetables, and is highly valued for this purpose. Some of the more fibrous sedge peat is also used for similar purposes, but much of it is not so used because of drainage problems and shallow depth to bedrock. Large acreages are now reserved for use as a park and for wildlife.

Pacific Coastal Valley area

(1) Geographic setting and climate. In the semiarid Pacific valleys, peat and muck are developed extensively in the tule marshes of the Klamath Plateau of northern California and southern Oregon, and in the delta peat land at the confluence of the San Joaquin and Sacramento rivers. The low rainfall and hot summer favor the accumulation of soluble salts.

(2) Native vegetation. Tules, reeds, sedges, rushes and aquatic plants abound.

(3) Soils. The Klamath tule peat is characterized by brown fibrous, porous, and poorly-decomposed plant remains. Below this are gray fine organic sediments, consisting principally of the shells of diatoms with an admixture of volcanic ash.

The Sacramento–San Joaquin delta area consists of numerous peat islands where originally a dense growth of tule, reeds, and aquatic plants grew. Most of the islands developed in open water and represent lake-filled types of considerable thickness; others accumulated on flat land and were built up under conditions of a rising water table.

(4) Use. Drained areas under cultivation and irrigation in the Klamath district produce good yields of alsike clover, rye, barley, and grasses initially, but yields decline when evaporation lowers the groundwater level and salts accumulate.

The islands of the delta district are now under cultivation and protected from overflow by levees. Three types of peat were listed by the U.S.D.A. One is yellowish-brown, coarsely fibrous, porous reed peat, commonly known as buckskin peat, which was not considered satisfactory for agricultural crops. A second is a reddish-brown fibrous tule-reed peat, which is fertile and productive for potatoes, sugar beets, asparagus, onions, and other intensively-grown crops. The third is described as a dark-brown sedimentary and sedimentary-fibrous peat that is comparatively dense, not easily drained and cultivated, but productive under good management. In the virgin condition the surface elevation of the peat islands was near level, but cultivation resulted in marked shrinkage.

Coastal marshland

(1) Geographic setting and climate. Coastal marshland occurs in scattered areas in tidal channels at the mouths of rivers, in quiet waters of lagoons, and behind barrier islands along the Gulf and Atlantic coasts. The rainfall is high during the summer, and prevailing coast winds from the relatively cool ocean waters accentuate the wetness of the growing period.

(2) Native vegetation. Dense growths of saltgrass, sedges, herbaceous plants, and shrubs abound; on the southern shores of Florida the mangrove, an evergreen shrubby tree, predominates.

(3) Soils. The surface materials usually consist of yellowish to reddish-brown, coarse, fibrous and matted peat, porous and permeable, gradually built up over black clayey mud flats or gray loose sand by accumulation of plant remains. Gradations from salt-water to brackish and fresh-water types are encountered.

Vegetation in areas subject to high tides and wave action or river currents retards the silt-laden overflow, allowing the mineral material to mingle with the mass of roots. The surface material is accordingly more or less compact, impermeable and plastic, bluish-gray, mottled with iron stains, and may be underlain by fibrous peat that releases hydrogen sulfide.

(4) Use. Coastal marshland peats, when drained and cropped, undergo decomposition and a long-continued shrinkage, as do all peats. The subsidence often makes drainage a problem. In its natural condition, coastal marshland serves as a haven for birds and other wildlife.

CLASSIFICATION OF ORGANIC SOILS

For those interested in the classification of organic soils, reference should be made to the paper by Farnham and Finney (1965). They reviewed the criteria used by various soil scientists in classifying organic soils, and pointed out some of their shortcomings. They considered that most of these classification schemes are far from satisfactory, largely because they are based primarily on theoretical concepts and "have little value in making accurate maps of important land resources." They propose their own classification system, designated as an approximation, which is in close alignment with that suggested by the U.S. Soils Survey Staff for mineral soils (see Smith, 1960).

REFERENCES

Anderson, M.S., Blake, S.F. and Mehring, A.L., 1951. *U.S. Dep. Agric. Circ.*, 888: 1–31.

Boelter, D.H., 1964. *Soil Sci. Soc. Am., Proc.*, 28: 433–435.

Boelter, D.H., 1966. *J. Soil Water Conserv.*, 21: 50–53.

Broadbent, F.E., 1960. *Hilgardia*, 29: 587–612.

Burke, W. and O'Hare, P.J., 1962. *Trans. Jt. Meet. Comm. IV, V, Int. Soil Sci. Soc., N.Z.*, 647–655.

Dachnowski, A.P., 1919. *U. S. Dep. Agric. Bull.*, 802: 1–40.

Dachnowski-Stokes, A.P., 1933. *U. S. Dep. Agric. Circ.*, 290: 1–30.

Davis Jr. J.H., 1946. *Fla. Geol. Surv., Geol. Bull.*, 30: 1–247.

Dawson, J.E., 1956. *Adv. Agron.*, 8: 377–401.

Farnham, R.S. and Finney, H.R., 1965. *Adv. Agron.*, 17: 115–162.

Feustel, I.C., 1938. In: *Soils and Men – Yearbook of Agriculture, 1938.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., pp. 462–468.

Feustel, I.C. and Byers, H.G., 1930. *U.S. Dep. Agric. Tech. Bull.*, 214: 1–26.

Feustel, I.C. and Byers, H.G., 1936. *U. S. Dep. Agric. Tech. Bull.*, 532: 1–25.

McDowell, L.L., Stephens, J.C. and Stewart, E.H., 1969. *Soil Sci. Soc. Am., Proc.*, 33: 743–745.

Rigg, G.B. and Gessel, S.P., 1956. *Soil Sci. Soc. Am., Proc.*, 20: 566–570.

Robinson, W.O., 1930. *Soil Sci.*, 30: 197–217.

Smith, G.D. and U. S. Dep. Agric. Soil Surv. Staff, 1960. *Soil Classification – A Comprehensive System, 7th Approx.* U. S. Dep. Agric., 265 pp.

Soil Survey Division, U.S. Dep. Agric., 1938. *Soils and Men. – Yearbook of Agriculture, 1938.* U.S. Govt. Printing Office, Washington, D.C., pp. 1019–1161.

Szalay, A. and Szilágyi, M., 1968. *Plant Soil*, 29: 219–224.

Waksman, S.A., 1942. *N. J. Dep. Conserv. Dev., Geol. Ser. Bull.*, 55: 1–155.

Waksman, S.A. and Stevens, K.R., 1928a. *Soil Sci.*, 26: 113–137.

Waksman, S.A. and Stevens, K.R., 1928b. *Soil Sci.*, 26: 239–252.

Chapter 30

THE USE OF PEAT FOR CROP PRODUCTION

INTRODUCTION

In the preceding chapter it was pointed out that peats vary markedly in properties and in their suitability for use for various purposes. Many of the deposits are of little or no agricultural value for a variety of reasons, including physical nature, lack of adequate decomposition, impossibility of providing satisfactory drainage, inadequate depth, toxicity, etc. Most of these peats are, however, serving a valuable purpose as wildlife reservations or parks, and sometimes for water storage.

Many of the better peats are being cropped intensively after preliminary treatment as necessary to make them into a satisfactory medium for plant growth. Some of our most valuable soils are peats and mucks. In addition, many tons of peat are now being sold for use as a humus source in mixture with mineral soils. The principal problems involved, and the best methods of using organic soils for plant growth, and for the improvement of mineral soils in gardening operations, are discussed in this chapter.

CROPPING ORGANIC SOILS

Drainage

The first step in the reclamation of a peat bog or soil for the profitable production of crops is to provide adequate drainage. This may require the construction of drainage canals, as in the Florida Everglades; in less extensive peat deposits small open drainage ditches into which tile drains may empty are adequate. Since peats retain so much more water than do mineral soils, and are located in low places, it is especially important that both the tiles and the ditches be of sufficient capacity to permit rapid removal of the excess water that drains from the higher areas. The proper laying of the tile often presents problems. Since peats undergo marked shrinkage due to compaction, oxidation, and sometimes wind erosion or fire, it may be necessary to relay the tiles at a lower depth after a period of 15 to 25 years. If the peat is comparatively shallow and the tile is laid in the subsoil, drainage may be poor because of the impervious nature of the mineral soil in which it is placed.

Preparation for crops

The steps necessary to bring a peat bog under cultivation, aside from drainage, vary with the nature of the peat itself and with the kind of living and dead plant cover present. Much of this cover is likely to be trees and shrubs. Whatever this vegetation may be, the first step is the removal of all of the coarse debris, including stumps and roots, from the drained area. Following this, it has been a common practice in some countries to burn off the remaining surface coarse material at a time when the deeper layers are too wet to burn. Unless such a procedure is absolutely necessary, however, a better practice is to cultivate the soil a few times to loosen it and to hasten oxidation of the upper 6–10 inches of true peat plus the undecomposed parts of the more fragile portions of the peat-forming plants. If the peat layer is very shallow, it may be advantageous to practice deep plowing so as to mix some of the clay subsoil with the peat. These plowing operations, whether deep or shallow, serve to convert the peat into a material that behaves much like a mineral soil.

A newly-reclaimed peat bog is usually an unsatisfactory medium in which to grow cultivated crops. The reasons include lack of aeration and oxidation, especially of the lower layers. Peat bogs have been under anaerobic conditions for centuries, and the roots of cultivated plants do not thrive in, or even penetrate, such an environment. This is due in part to lack of adequate oxygen, but often also to the presence of toxic amounts of such substances as ferrous iron, manganese compounds, sulfuric acid, and possibly soluble aluminum. Methane, hydrogen and sulfides are also likely to be present, at least in traces initially, but are no longer formed when oxygen is abundant.

After the initial drainage, clearing and plowing operations, it is usually a good practice to seed to suitable grasses and leave the soil in pasture or hay for two or more years. This can be followed by small grain crops until the soil is suitable for general cropping.

Poor plant growth on raw peats is also frequently due to high acidity and to nutrient deficiencies, discussed in the following section.

Nutrient deficiencies

In the consideration of peat for crop production, it is well to emphasize that there is usually a marked difference between raw peat and peat that has been drained and well aerated for some time. As Dachnowski-Stokes (1926) states: "In the raw state all types of peat of whatever stage of previous disintegration have a low value as nutritive constituents. . . . . . When properly aerated, cultivated, and mineralized, the change from the peat stage to a material resembling humus may take place rapidly." Even good, well-aerated organic soils usually need fertilizers, but which elements, and how much, varies with the soil and crop, as is true of mineral soils.

Burke and O'Hare (1962) summarize the situation as follows: "In practically all peats the levels of all major and minor elements are inadequate for satisfactory crop production. After drainage, successful conversion to productive land depends largely on the application of adequate balanced fertilizers. Workers in many countries have shown that liberal dressings of the major elements are required at the outset and that these must be supplemented annually by lighter dressings. It is also necessary to overcome the deficiencies of minor elements that invariably arise, particularly in the early stages of development. While different crops require minor elements in varying degree, copper, molybdenum, boron, zinc, and manganese appear to be of particular importance." On highly acid peats toxic effects may be encountered even from low levels of some heavy metals.

Lime deficiency is characteristic of most sphagnum and woody peats. As already stated, the pH of these peats commonly lies between 3.0 and 5.0, which is in a region too low for the growth of all but the most acid-tolerant plants. Cultivated crops prefer a pH between 5.0 and 7.0. There is some uncertainty as to whether a very low acidity inhibits directly, or whether poor growth results primarily from lack of the proper nutrients, especially calcium (lime). Undoubtedly, both pH and nutrient deficiencies are important, but pH as such seems to play a secondary role. More important is likely to be lack of calcium, magnesium and potassium in acid peats. Addition of lime alone certainly goes far toward making a very acid peat a satisfactory growth medium initially, but with further cropping magnesium and phosphorus are likely to become deficient. The need for these elements will be less likely to appear on lowmoor peats that are better supplied with basic elements. The reed, sedge and sedimentary peats, formed in bogs, ponds and marshes, have usually been supplied with adequate basic materials derived from the mineral soils on which they were formed, or which were brought in through drainage from higher areas.

Minor element deficiencies are also encountered frequently in cultivated peats or mucks. In the Florida Everglades it was lack of copper that accounted for retarded plant growth originally (Allison et al., 1927). But now, after years of cropping and copper additions, this element is present in some areas in such amounts as to be toxic to certain crops. This may be attributed primarily to the marked subsidence of the peat (approximately an inch per year) with a resulting concentration of the added copper. The element probably chelated with the peat when added, thus accounting for the fact that it has not been removed to any appreciable extent in the drainage waters over the years. The need for minor elements other than copper, such as zinc and boron, have not been so strikingly demonstrated, but do exist for certain peats, especially after years of cropping.

Highmoor peat soils of New Zealand, formerly considered as waste lands, have, as a result of research by Hupkens van der Elst (1962), been shown to be capable of being used as high-producing pastures. Additions of lime, phosphorus, potassium, and nitrogen, as well as copper, molybdenum, and sometimes iron, are required. Zinc and boron are also needed by certain crops.

Productivity

Peat soils, when properly managed, are considered as our most productive soils. This productivity may be attributed in large part to the comparatively high nitrogen content of most peats and to the abundant colloidal organic material – two substances generally recognized as closely associated with abundant plant growth.

The nitrogen content of most of the cultivated peats in the United States ranges between 2 and 3.5%. These are lowmoor and aquatic peats. The sphagnum and forest peats usually contain 1.5% or less of nitrogen, reflecting the low nitrogen contents of the plants from which the peats were formed. The higher nitrogen contents of the lowmoor and aquatic peats reflect similarly the plants from which they were derived, but in addition these peats were formed under conditions of more abundant nitrogen supplies to the native vegetation. The waters in which the sedges, reeds, grasses and shrubs grew contained nitrogen leached from higher areas in many instances. Furthermore, these bog plants undoubtedly benefited at times from the activities of nitrogen-fixing blue-green algae, bacteria and alders. As the bogs became filled with organic debris, the conditions may have been such as to permit even a few legumes, including trees, to grow for a time.

Nitrogen is present in peat in various forms not well understood. A considerable portion is known to be in the form of protein, but not in a free state. It is complexed with lignin, cellulose and hemicellulose. In such forms it is not readily released as ammonia, but does undergo slow release as the peat decomposes. It is very fortunate that it is not readily released, because in this age of abundant supplies of commercial synthetic ammonia, the nitrogen is far more valuable to agriculture when present as complexes than if present as ammonia.

The addition of nitrogen fertilizers to well-decomposed peats or mucks, except to those extremely deficient in this element, is usually not necessary for good crop production. The normal rate of oxidation that continually goes on under cultivation is commonly adequate to release the amount of ammonia required by most crops. Where it is demonstrated that additional nitrogen is needed for good crops, additions may be made in accordance with the same principles that apply to its use on mineral soils. If applied as ammonia and not utilized promptly, it will be converted into nitrates rather rapidly during the growing season if the pH is satisfactory. Peat soils are normally good nitrifiers.

Studies made by Neller (1944a) on Everglades peat, where the water table was controlled, showed that the conversion of the nitrogen of the peat to nitrates was rapid. There was no indication that crops would have responded to a nitrogen fertilizer, except possibly for brief periods following a long rainy period. During dry periods nitrates were adequate for crops even where the water table was held at a depth of 12 inches. In less-decomposed, low-nitrogen, sphagnum moss peats it is likely that nitrogen fertilization might be profitable at certain times.

The use of animal manures on peat soils as a means of supplying nitrogen is likely to be an unprofitable procedure. If such manures are available for use, they should be applied to mineral soils where the organic matter, usually the most valuable constituent, will exert its maximum effect. About the only time that animal manures should be applied to a peat soil is when the peat is being reclaimed from the bog and put under cultivation. In this case the manure serves as an inoculant and may perhaps be of some value. Ordinarily, however, soil inoculation, except for legumes, is unnecessary.

Another reason why peat soils are productive is the fact that they are readily penetrated by roots, and an extensive root system forms if the water table is not too high or the peat too compact. In addition, the presence of this water table assures that the plants will have an adequate moisture supply throughout the growing season. Constant decomposition, and the presence of chelated elements, also assure an adequate supply of available nutrients as needed. Even the carbon dioxide continually released is partly absorbed by the plant roots and leaves, and becomes a part of the plant substance.

Crops

Most field crops, such as corn and small grains, will not grow satisfactorily for the first two or three years on a newly-drained peat soil. After the initial one or more plowings and a few cultivations to promote aeration, a recommended procedure for new peat soils is to sow a grass–clover mixture and use it for pasturing livestock. After a year or more of such treatment small grains, and even corn, may be grown satisfactorily. The crops to be grown initially will of course vary with the peat, the region, and the climate.

After a peat has been fully reclaimed, almost any of the common field and garden crops can be grown satisfactorily. Corn, sugar cane, small grains, grasses, and legumes grow well if the pH, nutrient levels and water table are adjusted to suit the crop. Especially good results have been obtained with onions, celery, radishes, cabbage, potatoes, beans, and most other garden crops.

Peat soils are also suitable for the growth of special crops that require an acid reaction. The two chief ones are blueberry and cranberry. The cranberry is usually grown on wet, acid soils that are unsuitable for the growth of most agricultural crops. Other peat lands that are marginal with respect to general cropping may usually be used for reforestation, or sometimes for pasture.

Temperature relations

Peat soils are considered as cold soils because the surface portion and the air above usually have a lower temperature than mineral soils in the same locality. Peat soils hold much water and are located at the lowest elevations, and of course cold air accumulates in depressions. In addition, peat is a much poorer conductor of heat than mineral soils, and hence the transfer of heat upward from the subsoil is slow. Heat moves fairly rapidly in moist peat, or in mucks, but dry loose peat acts as an insulation. These temperature relations are of great importance in regions such as Florida, where vegetables and fruits are being grown for the winter and early spring markets.

Subsidence and water table

When a peat is drained and prepared for cropping, a marked shrinkage takes place. This shrinkage is usually greater for the lowmoor than for the highmoor peats. The chief initial cause of shrinkage is physical compaction caused by the lowering of the water table and by operations involving the use of machinery in clearing and cultivating the land. Shrinkage of the organic colloids through loss of water, and biological oxidation, play lesser roles initially. After a few months, or years, a fairly stable equilibrium is reached but some subsidence continues at a fairly constant but ever-decreasing rate. This continuing subsidence is usually caused almost entirely by biological oxidation of the peat to carbon dioxide and water, although Rifle peat has been shown to lose some organic matter in the drainage water (Hayes and Mortensen, 1963). Since biological oxidation increases 2- to 3-fold for each 10°C increase in temperature, it would be logical to expect the subsidence to be considerably greater in Florida than in the same type of peat in Maine or farther north. In fact, Stephens (1956) states that the average subsidence rate of about 1.25 inches per year in Florida is about double that found in similar studies in Indiana. Rates of 3 inches per year have been reported for some California peats (Broadbent, 1960).

Albert (1946) reported that in Wisconsin, measurements starting 18 years after drainage showed that under an uninterrupted corn–grain–hay–hay rotation the rate of subsidence of an organic soil during the next 12 years was 0.34 inches per year; under almost continuous hay and pasture the subsidence was only 0.08 inches. These figures emphasize that subsidence can be low even in a well-drained organic soil, if the temperature is moderate and tillage operations are kept to the minimum. It is well to bear in mind, however, that peat may have up to 50% mineral matter on a dry weight basis, and muck 50–80% mineral matter (Stephens, 1955). Comparative subsidence figures for various organic soils are, therefore, not very meaningful unless the organic-mineral relationships are known.

Clayton et al. (1942) stated that most soils of the northern Everglades had then subsided about 5 ft. since they were drained about 25 years earlier. Much of the peat in the northern Everglades region was 8–12 ft. deep initially, decreasing in depth toward the south. Fig. 30.1 shows the rate and extent of the shrinkage during the period of the study. During the first 2 or 3 years the shrinkage was very marked, but after about 4 or 5 years had become rather constant at nearly one inch per year. The present rate is not

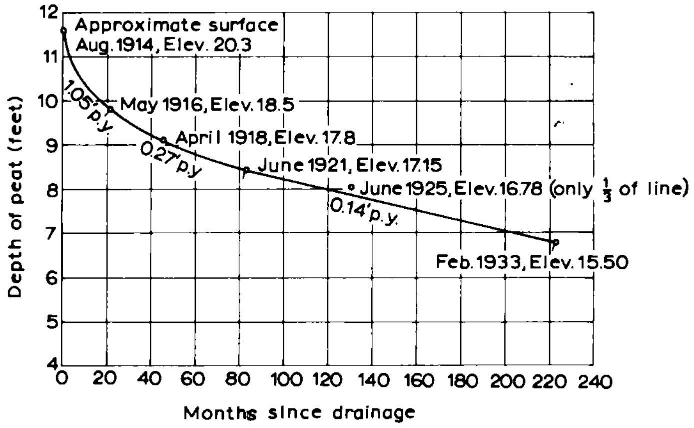

Fig. 30.1. Surface subsidence of Okeelanta peaty muck near the Bolles Canal, Florida. (From Clayton et al., 1942.)

much less for this sawgrass peat, but is somewhat less for the muck soils in the Okeechobee region. Many of these highly productive soils are now less than 3 ft. deep, and are underlaid by limestone and not mineral soil. It is obvious, therefore, that such soils now have a limited life (see Jones, 1948).

Studies made in the Florida Everglades over a period of 5 years by Neller (1944b) showed that the rate of oxidation of peat, as measured by carbon dioxide production, was closely correlated with the height of the water table. Carbon dioxide evolution was approximately 9 times greater with a 24-inch water table, and 14 times greater with a 36-inch water table, than with a 12-inch water table. Oxidation of an unplowed peat with a 24–36 inch water table was equal to that of a cultivated peat with a 36-inch water table. This emphasizes the major importance of aeration and the lesser importance of cultivation. Neller's results also show that subsidence during the experimental period was brought about almost wholly by the loss of the peat through oxidation.

Clayton et al. (1942) estimate that the average water table in the cultivated soils of the northern Everglades is about 2.5 ft. They state that if the water table were held to an average depth of 1.5 to 2.0 ft., the subsidence could be decreased markedly. This seems to be the only practical way of decreasing the soil loss, but factors other than oxidation and subsidence must be considered. Aside from the engineering and hydrology features, is the fact that some crops do not grow satisfactorily with a high water table. In addition, the water may make the soil too soft to support heavy machinery.

In work done in southern Ontario, Mirza and Irwin (1964) found that the rate of subsidence of a soil on the Holland Marsh, where no water control program was followed, was 1.3 inches per year. This is a rather high rate for an organic soil having an average depth of 3 ft. and frozen for 5 months of the year.

In controlled experiments (Harris et al., 1962) in northern Indiana, average subsidence rates of 0.79 and 0.36 inches per year were observed for 40- and 16-inch water tables, respectively. The subsidence rates decreased with time. The yields of onion, potato, peppermint, carrot and corn were greatly reduced by a 16-inch water table as compared with yields obtained on 24-, 32- and 40-inch water tables. Nitrogen fertilizers increased crop yields only on the 16-inch water table.

In many areas, such as the glaciated Corn Belt, it is common for organic soils to be underlaid with fertile mineral soils, and profitable farming can continue even after the muck is all gone, provided of course that adequate drainage can be provided for these depressed areas. In many of these areas no control of the water table is provided, and fires may be a problem in dry years.

Management

Most of the management problems connected with the farming of peat and muck soils that have been in use for several years revolve around water table adjustment, prevention of blowing and fires, and fertilization. These points and others are discussed in some detail by Harmer (1941).

If the drainage system is such as to allow adjustment of the height of the water table, then water management presents no great difficulties. In general, the water table should be at the maximum height that will permit the normal growth of the crop and allow the movement of farm machinery. This height will vary somewhat with the nature of the peat, whether very fibrous or woody or more of a sedimentary or muck type. The height will also vary with the crop, especially the length of its root system. Crops such as radishes, spinach and other quick-growing vegetable crops can tolerate a higher water table than can the longer-rooted corn.

Wind erosion and fires are often a problem during very dry periods where the water table is low. Blowing of peat cannot be completely prevented, but is greatly minimized by keeping a growing crop on the soil during the period when such erosion is likely to occur. The planting of a quick-growing crop of soybeans or cowpeas to serve as a catch crop between cash crops may be effective.

Where provision has been made for water table adjustment, it is often advisable to raise the water level at times when a crop is not present. This practice retards the destruction of the peat by biological oxidation as well as helping to minimize fires and blowing. Where no such adjustment is possible, it is not unusual for fires to burn slowly for days during dry periods, and in extreme cases destroy the entire peat layer.

Proper fertilization presents few problems not common to mineral soils. In both types of soil, the first and most important thing is to know the kind and extent of the soil deficiency, and then to adjust the fertilization to fit the cropping system. The needs for nitrogen, as already stated, vary widely. In the use of phosphates and potash it is well to bear in mind that a peat soil does not fix these to the same extent, or in the same way, that mineral soils do. This emphasizes the desirability for adjustments in rates with time as well as with crop. In the use of minor elements careful adjustments may also be needed, since these elements are chelated with the peat colloid and held in an available form to a much greater extent than is true in mineral soils.

THE USE OF PEAT FOR MINERAL SOIL IMPROVEMENT

The use of peat for agricultural purposes on mineral soils has increased at a rapid rate during the past few years. This is evidenced by the piles of bagged and baled peat that now decorate the entrances to our chain grocery stores, garden supply houses and nurseries. Most of this peat is utilized in city flower and vegetable gardens and greenhouses. It serves a variety of purposes as outlined here.

According to Dyal (1960) more than half a million tons of peat were being sold annually in the United States at that time for soil improvement. The average dry organic matter contents of the 26 peats examined were for bulk 26.6%, bale 66.4%, and moisture-proof packages 37.7%. The average ash contents on an oven-dry basis and in the same order were 17.5%, 1.4% and 16.6%. Only 3 of the peats had a pH as high as 7.0, and 7 were below pH 4.0.

Kinds of peats

Two kinds of peats, namely reed or sedge and mixtures of these, and sphagnum peats, are in common use in the United States. The bulk of the material sold is of the reed or sedge type. This is partly because this is the most abundant type available, but it is also more suited for a wide variety of uses in mixtures with soil.

Non-woody lowmoor types of peat are usually only moderately acid, have good textural characteristics when shredded, retain large amounts of moisture, and are better supplied with nitrogen and other plant nutrients than are the moss peats. These peats serve as fairly satisfactory substitutes for stable manure and well-rotted compost, although the available nutrients released during the first six months from the two types of materials are very different.

Moss peats may also be used in mixture with soil, just as are the reed and sedge peats, but they are less satisfactory for this purpose. The moss peats do retain more water but they are more fibrous, resist decay, have lower contents of nutrients, and are more acid. Where sphagnum peats are so used it is essential that they be reinforced by additions of complete fertilizer, and also lime, unless the most acid-loving types of plants are to be grown.

Direct use in mixture with soil

Peat or muck is used in mixture with soil for the following chief reasons: (1) improvement of the physical conditions (tilth); (2) increasing the water-holding capacity; (3) as a humus and nutrient source; and (4) to provide a better rooting medium. The benefits to be derived from the use of such a material depend very much on the properties of the soil, especially on its texture and natural supply of organic matter. Usually the greatest benefits follow the addition of peats to very sandy soils and to very impervious clays; the least benefits are realized from use in mixture with loams that are already well-supplied with organic matter.

Tilth

Many soils that are in fairly good physical condition, and can be cultivated easily when at optimum moisture, often become hard and impervious when dry. This may be true of both sandy and clay soils, but especially of clays. The latter may also become very sticky and remain for some time in a condition such that cultivation is not possible. The movement of water through such clay soils is also likely to be slow for best plant growth. The addition of a well-decomposed peat or muck to such soils at rates of one-sixth, one-third, or more by volume will go far towards making such soils, both sands and clays, nearly ideal for tillage. The initial effects are similar to the addition of very heavy applications of thoroughly-rotted manure, but peat is far more durable.

Fresh plant materials added to soil are commonly oxidized to the extent of 70–80% in one season, and animal manures to 50–60%. Peat, on the other hand, is a decay-resisting material and 90% of it is likely to remain for the second growing season. The physical benefits derived from peat additions may be expected to be in evidence for several years after treatment.

Water absorption and retention

All peats have a much higher capacity for water absorption than do mineral soils (see Table 29.V). This table shows that peats in their natural condition can absorb and hold 3 to 27 times their weight (dry basis) of water. Morgan (1940) reported a similar range of moisture-holding capacities for 17 peats that he studied. The higher values are for sphagnum peats and the lower for mucks that are free of fibrous materials and higher in mineral matter. When such materials are mixed with soil, the increase in water-holding capacity is marked. Morgan's studies showed that a mixture of three volumes of sandy soil to one of peat contains 50–100% more water when saturated than the sandy soil alone. The increase in water-holding capacity would be less for fine-textured soils. Similar results, reported by Feustel and Byers (1936), are shown in Table 30.I.

The decrease in bulk density of a soil produced by the addition of peat, plus the ability to hold much larger amounts of water, are factors that can have a marked effect on water absorption under field or garden conditions. Even the hardest rains can usually penetrate the peat–soil mixtures, where in the absence of the peat a heavy runoff would be expected. There is one possible exception to this statement. Thoroughly dry peats are sometimes difficult to wet quickly, but as they gradually take up moisture they tend to act like a sponge. This slow wetting is in evidence when the peat is used as a mulch, but when mixed with soil in the usual proportions the peat is rarely so dry as to lose its ability to take up water readily.

Feustel and Byers determined the moisture-holding capacities and wilting percentages of three peats and two soils, and of mixtures of these. A portion of these data is shown in Table 30.I. From these data the available moisture has been calculated and expressed as percentage of the moisture-holding capacities of the various materials and mixtures.

The wilting percentage is the quantity of moisture held by a soil or peat at the time that plants (in this case sunflowers) undergo permanent wilting. Column 4, Table 30.I shows that the percentage of unavailable moisture remaining in the peats at the wilting stage were for moss peat 82.3, reed peat 70.7 and sedge peat 60.8; the corresponding value for the clay loam soil was 7.1 and for the loamy fine sand 2.1. The soil–peat mixtures gave values approximately additive for the constituents. These marked differences in wilting percentages between the peats and soils emphasize the frequently-made statement that even though peats absorb large amounts of moisture a considerable portion of it is unavailable for plant use. Although this statement is correct, it is misleading when considered from the practical standpoint, where we are concerned primarily with the volume occupied by peat and not with its dry weight.

Reference to the data in Table 30.I shows that moss peat, which had a wilting percentage 11.6 times greater than that of the clay loam soil, retained approximately the same amount of moisture when the comparison is made on a volume basis. The sedge and reed

TABLE 30.I

MOISTURE-HOLDING CAPACITIES AND WILTING PERCENTAGES OF PEAT AND SOIL, AND OF MIXTURES* OF THESE (from FEUSTEL and BYERS, 1936)

Material	*Weight of 100 cm³ of air-dry material (g)*	*Moisture-holding capacity (%)*	*Wilting percentage (%)*	*Available moisture as percentage of moisture-holding capacity (%)*	*Moisture required to saturate 100 cm³ of dry material (g)*	*Moisture retained by 100 cm³ of material at wilting point (g)*
Moss peat	11	1057	82.3	92.2	101	8.0
Sedge peat	27	374	60.8	83.7	91	15.0
Reed peat	39	289	70.7	75.5	99	24.0
Clay loam	109	44.3	7.1	84.0	48	7.7
Loamy fine sand	135	30.9	2.1	93.2	42	2.8
Clay soil-moss peat mixture	60	114	14.5	87.3	67	8.5
Clay soil-sedge peat mixture	68	95.7	19.2	79.9	63	13.0
Clay soil-reed peat mixture	74	94.1	21.2	77.5	67	15.0
Sandy soil-moss peat mixture	73	101	6.6	93.5	73	4.8
Sandy soil-sedge peat mixture	81	80.8	13.5	83.3	64	11.0
Sandy soil-reed peat mixture	87	79.3	16.2	79.6	67	14.0

*All mixtures were 50% peat and 50% soil on a volume basis.

peats, when compared on the volume basis, held 2 to 3 times as much moisture at the wilting point as did the moss peat, although their wilting percentages were lower. This may be attributed to their more decomposed condition and larger percentage of colloidal constituents.

The moisture-holding capacities, and percentage of this that is available for plant use, are also given in Table 30.I for the peats, soils and mixtures. It will be seen (column 5) that the values range between 75.5 and 93.5. The value for moss peat is similar to that for the sandy soil and actually 8% higher than for the clay loam. The colloidal reed peat held the water most tenaciously. Evidently the water absorbed by peats, especially the more fibrous types, is not as unavailable for plant use as many have believed.

Humus source

Peat is used in mixture with mineral soil primarily as a humus source and a substitute for animal manures and compost. The many functions of humus have been discussed in preceding chapters and need not be reviewed here. As a humus source, the more decayed types of peat and muck, rather than moss peats, are most satisfactory. They are high in colloidal constituents, and in many respects act as does humus formed from other plant sources. The chief thing to bear in mind is that they are often deficient in plant nutrients, especially phosphorus, potassium, calcium, magnesium and some trace elements. It may or may not contain adequate nitrogen for good crop growth, depending on the source of peat and its stage of decay. The needs for all the nutrients vary so much with source that general statements are not justified. Fertilizer tests give the best answer to the problem.

Peat was often used in earlier years as both a humus source and as a fertilizer, with the expectation that it would give results similar to those obtained with animal manures. Although increased yields were often obtained, and the physical condition of the soil was improved, it did not act like animal manures. This was due in part to deficiencies in mineral nutrients, but to a greater extent to the comparatively inert nature of the material. As already pointed out, manure is an active material and as it decomposes, nutrients are constantly released through biological action. In contrast, peat is so resistant to decomposition that much of the release of nutrients must be through exchange reactions and as chelated elements.

Since peat is resistant, it is also less likely to improve tilth and soil structure by direct chemical linkages, as do artificial soil conditioners. It does serve to loosen and aerate clay soils and make cultivation easier. It also supplies colloid to sandy soils, thereby making them less compact and increasing the inorganic colloid content that is so much needed.

Root extension

Peat in mixture with soil, and adequately supplied with nutrients, serves as an excellent medium for root growth if it is not too acid. In very compact soils growth is often curtailed because of the inability of roots to penetrate them readily. Peat corrects this and in addition releases nutrients that favor root development. Root penetration into the subsoil is often curtailed because of either the presence of a hardpan, lack of calcium, or too much soluble aluminum. The addition of peat is not likely to correct these conditions unless it is mixed with the subsoil. Where this can be done, a comparatively small amount of peat, reinforced with the needed nutrients, may have a long-term effect in correcting the unfavorable condition.

Compost

Shredded peats, either lowmoor or highmoor, are excellent materials to be used in mixture with various vegetable wastes and manures in compost piles. They serve as a partial substitute for garden soil that is commonly used. In the compost pile the peat undergoes some slow changes which make it more suitable for garden and greenhouse use (Snyder and Wyant, 1932; Wieringa, 1963, 1964). It also aids in the composting process through its water-holding capacity, its deodorizing properties, and its ability to absorb and hold ammonia. It keeps the compost pile better aerated, thus favoring the decay of other materials present. Finally, it adds bulk to the final product and helps to give the compost more nearly ideal physical properties. Peat taken directly from the bog, even though shredded and supplied with lime and other essential nutrients, may prove to be too toxic for best use. Some preliminary treatment may be needed to make this material suitable for use in compost piles.

The economic aspects of use of peat in composts should usually be considered. Unless a local low-cost supply is available, it is seldom advisable to use the material in this way. Uncomposted, but chemically reinforced peat, is often about as good as the far more expensive composted material, and can be obtained more readily. Compost is usually considerably more biologically active than peat, but this increased activity is not always needed or desired. The final use of the material is the determining factor.

Greenhouse

Peat is a very essential ingredient for use in mixture with soil for the growing of various plants in pots and on greenhouse benches. A sedge or reed peat is usually preferred for this purpose. A common mixture is about one part of peat by volume to two or three of a good sandy loam soil. If the soil tends to be a little heavy, an addition of some sand may be advisable. It is sometimes beneficial to add a small amount of manure to supply an active biological flora. Usually little extra nitrogen is needed if the lowmoor peats are used, but it is essential that lime, phosphates and potash be added, if needed. Minor elements are sometimes deficient.

A peat–soil mixture is an ideal medium both for starting seedlings and also for growing them to the desired stage of maturity. The young plants can be removed readily from such a medium without severe root disturbance, thereby minimizing the shock of transplanting. If in pots, the entire contents of the pot together with the seedling may be readily transplanted to the garden.

Cuttings of various plants, including softwoods and hardwoods, that are often difficult to root in sand can be rooted more readily in peat. Sphagnum peat seems to be preferable for this purpose.

Gardens, lawns and golf courses

The use of peat for soil improvement in the open is usually limited to gardens, lawns and golf courses, because of the cost. The best practice is to apply an inch or so of sedge or reed peat to an area that is to be seeded, and work it into the upper few inches of soil. Any fertilizer or lime that is needed can be applied at the same time if grasses are to be sown. If vegetables, flowering plants, or shrubs are to be grown the fertilizer may be applied later in the row or hill if desired.

Top-dressing of lawns with peat is usually not very satisfactory, because only limited amounts can be applied at any one time without smothering the grass. Furthermore, this system fails to get the material into the soil where it is most effective.

The need for organic matter is especially great following building operations that often cover the topsoil with subsoil. The incorporation of peat with such subsoils is one of the best ways of getting them so that grasses can get a start, probably after one or more cover crops have been grown initially.

The problem of establishing a good sod on golf greens is an especially difficult one because the soils have often been graded, or are naturally poor. The requirements for a good green are also very exacting. The details of how peat may be used to meet this problem are discussed by Monteith Jr. and Welton (1933). It is essential that the quantity of peat used should not be such as to make the green too soft and spongy. Neither should the soil be such as to become too hard on the surface when it is dry. Usually the use of 15–30% of peat by volume, worked into the soil before seeding to grass, will give satisfactory results.

Mulches

The more fibrous types of peat may be used to advantage as mulches for flowers, shrubbery and other plants. The more acid peats are suitable for use around rhododendrons, azaleas, and any acid-loving plants. The more decomposed types of peats and mucks are less suitable as mulches, because of the difficulty in wetting them and because of their tendency to float or blow away. The slow-wetting qualities may also interfere with infiltration and favor runoff. This is much more apt to occur where peat is used as a mulch than if mixed with even a small portion of the surface layer of soil.

Thin layers of peat placed on a newly-seeded area of grass or vegetable crops provide an excellent system for insuring germination and good seedling growth. Such a covering prevents soil crust formation and insures adequate soil moisture for germination, except during the driest periods.

On city lots or other small areas, lawns can be started in the warmer months of the year without great difficulty, contrary to the usual recommendations, if a suitable seedbed is prepared and a light covering of peat is spread over the seeded area. This must be watered lightly with a fine spray, two or three times a day, depending on the weather and the intensity of the sunlight. Within about a week (instead of 2 to 4 weeks in the fall) the seed will have germinated and the wetting process can then be reduced to once a day, and shortly to only two or three times a week or less, if rains occur. During the first two weeks at least, the fine spray should be applied uniformly to the surface for only a short time, and never with sufficient intensity as to cause displacement of the seed or peat. The thin layer of peat serves to cover the seed, keep them moist, and act to a minor extent as a mulch. The writer has used this procedure repeatedly on small areas with success. It is an excellent one, but only if the gardener has the time and patience to apply the water carefully, and often enough to keep the seed moist until germinated. It scarcely need be added that fall is the ideal time for starting lawns, but it is well to know that they can also be started at other times, and the addition of 0.1–0.3 inches of peat will go far toward assuring success of the operation. In fact, such a peat covering greatly facilitates the starting of a lawn even in the fall, especially if water applications are necessary at that time, and they are usually required.

Possible toxicity

Attention has already been called to the fact that raw peats as obtained from bogs are rarely, if ever, suitable for plant growth. If sufficient pre-treatment has not been given, the peats may give very unsatisfactory results when used in mixture with mineral soils. Any bad results are most likely to be due either to high acidity, nutrient deficiencies, or the presence of toxic substances. Little attention has been given to direct toxicity of peats commonly sold at corner stores, but there is increasing evidence that this factor needs to be given serious consideration. For example, in two successive seasons I set out high grade rosebushes, according to standard recommendations in a 3 to 1 soil–peat mixture that received agricultural lime and small amounts of complete fertilizer. The roses made almost no growth during the summer and were so nearly dead that they were removed at the end of the season. When new plants were placed in the same places the following year, they did not die but grew considerably less than did other roses that were set in the loam soil without additions of peat. From comments, as published on garden pages, I know that others have had the same experience. One person reported that he lost a hundred or so azalea plants that were set in a peat–soil mixture. Since these plants are acid-loving, a true toxic condition apart from acidity seems to be indicated although of course not proven. More attention may need to be given to assuring that the peats as sold are not toxic.

REFERENCES

Albert, A.R., 1946. *Soil Sci. Soc. Am., Proc.*, 10: 275–278.

Allison, R.V., Bryan, O.C. and Hunter, J.H., 1927. *Fla. Agric. Exper. Stn. Bull.*, 190: 1–80.

Broadbent, F.E., 1960. *Hilgardia*, 29: 587–612.

Burke, W. and O'Hare, P.J., 1962. *Trans. Jt. Meet. Comm. IV, V, Int. Soil Sci. Soc., N. Z.*, pp. 647–655.

Clayton, B.S., Neller, J.R. and Allison, R.V., 1942. *Fla. Agric. Exper. Stn. Bull.*, 378: 1–74.

Dachnowski-Stokes, A.P., 1926. *U. S. Dep. Agric. Bull.*, 1419: 1–23.

Dyal, R.S., 1960. *Soil Sci. Soc. Am., Proc.*, 24: 268–271.

Feustel, I.C. and Byers, H.G., 1936. *U. S. Dep. Agric. Tech. Bull.*, 532: 1–25.

Harmer, P.M., 1941. *Mich. Agric. Exper. Stn., Spec. Bull.*, 314: 1–128.

Harris, C.I., Erickson, H.T., Ellis, N.K. and Larson, J.E., 1962. *Soil Sci.*, 94: 158–161.

Hayes, M.H.B. and Mortensen, J.L., 1963. *Soil Sci. Soc. Am., Proc.*, 27: 666–668.

Hupkens van der Elst, F.C.C., 1962. *Trans. Jt. Meet. Comm. IV, V, Int. Soc. Soil Sci., N. Z.*, pp. 656–661.

Jones, L.A., 1948. *Fla. Agric. Exper. Stn. Bull.*, 442: 1–168.

Mirza, C. and Irwin, R.W., 1964. *Can. J. Soil Sci.*, 44: 248–253.

Monteith Jr., J. and Welton, K., 1933. *Bull., U. S. Golf Assoc., Green Sect.*, 13: 90–110.

Morgan, M.F., 1940. *Conn. Agric. Exper. Stn. Circ.*, 142: 85–96.

Neller, J.R., 1944a. *Soil Sci.*, 57: 275–280.

Neller, J.R., 1944b. *Soil Sci.*, 58: 195–204.

Snyder, R.M. and Wyant, Z.N., 1932. *Mich. Tech. Bull.*, 129: 1–63.

Stephens, J.C., 1955. In: *Water – Yearbook of Agriculture, 1955.* U.S. Dep. Agric., U.S. Govt. Printing Office, Washington, D.C., pp. 539–557.

Stephens, J.C., 1956. *Soil Sci. Soc. Am., Proc.*, 20: 77–80.

Wieringa, K.T., 1963. *Plant Soil*, 18: 53–69.

Wieringa, K.T., 1964. *Plant Soil*, 21: 333–344.

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