THE SOIL teems with microscopic life—bacteria, fungi, algae, protozoa—as well as being the home of many larger organisms. Each of these has its effect on the soil. The microscopic organisms especially are busy bringing about chemical and physical changes of enormous importance to man’s use of the soil. Among other things, they break down complex organic substances into simpler forms; they furnish nitrogen for plant growth. The work, beneficial or harmful, done by each kind of organism is described in this article.

Fauna and Flora of the Soil

BY CHARLES THOM and NATHAN R. SMITH

ROCKS, minerals, and elementary substances on the surface of the earth have been subjected to the corrosive power of the carbon dioxide of respiration and fermentation, to acids produced during the decomposition of successive crops of plant material, and to enzymes secreted by micro-organisms. The soil as we have it today is the cumulative result of ages of such attack, combined with the physical effects of weathering. Few substances added to the soil escape this solvent action. Among examples, metallic sulphur passes over into sulphide and sulphate; iron scatters in several directions; arsenic, selenium, and tellurium in contact with micro-organisms are transformed into vile-smelling gases. The sands of desert areas where the absence of water makes micro-organic life impossible represent soil materials without the presence of life which would transform them into soil. There is no true soil without organic matter, which may be classified as it exists in the soil into living and dead forms.

The organisms vary in size from the microscopic up to the gigantic and in numbers from a few per acre to billions per ounce. They have in reality changed the surface layer of the soil from an aggregate of mineral particles to a mass teeming with organisms and honeycombed by visible channels made by roots of plants or by burrows of animals and insects. There are, also, between the soil particles, invisible channels and spaces of various sizes, intricate networks of microscopic channels whose surfaces are smeared with colloidal slime, and a variable water solution carrying impalpable mineral and organic materials. The most numerous and the smallest of the plants are the bacteria,

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2 For a review of the literature on this and most of the other subjects mentioned in this article, the reader is referred to Waksman (145). Italic numbers in parentheses refer to Literature Cited, p. 1181.
which include forms barely visible under the microscope. The actinomycetes, molds, and algae are each larger but correspondingly less numerous than the preceding one. A similar gradation and correlation in size and abundance occur in the animal kingdom, the protozoa being the smallest and most numerous, followed by nematodes, worms, mites, and insects.

The micro-organisms are not evenly distributed through the pores of the soil. When they are independent of plant roots, bacteria commonly occur in colonies or clumps of a few to many thousands of individuals scattered along the walls of pores or channels in the soil or over the surfaces of soil particles. Molds produce tangled masses (mycelia) of threads (hyphae). Such colonies vary from a delicate network which may envelop one or a few soil granules to great masses of interwoven threads filling certain soil horizons over areas of hundreds of square feet.

THE PROCESS OF DECOMPOSITION

In addition to the micro-organisms that bear definite relation to the pores of the soil and to its mineral or organic constituents, great numbers representing many species are intimately related to the roots of green plants. Such organisms do not travel through soil seeking food but remain in constant association with the surface layers of the roots themselves. When the root hairs and the outer cells of the roots die, their decomposition is accomplished by the attack of these same molds and bacteria, which multiply to great numbers in the process. The ball of earth filled by the roots of a particular plant, with the micro-organisms that accompany them, is the center of very active biochemical activities involving great numbers of micro-organisms even while the plants are living.

The aerial portions of plants under normal conditions are also covered with a varied mixture of micro-organisms. When the plants die, are cut down, or are plowed under, this varied population, already in intimate contact with them, is ready to begin the progressive biochemical processes that carry plant and animal remains toward carbon dioxide, ammonia, and minerals. Plant residues enter the decomposition process carrying sugars, starches, hemicelluloses, celluloses, lignins, proteins, and fatty or waxy substances in percentages specific to their origin. Under favorable temperature and moisture conditions, the micro-organisms present on the material or in the soil quickly increase to fabulous numbers. Easily decomposed substances such as sugars, starches, and proteins disappear first. Celluloses, hemicelluloses, lipoids, and even the lignins are progressively broken down. Lignins, the most resistant, tend to linger, and together with the protein composing the bodies of the microbes they supply up to 75 percent of the dry weight of the final humus or soil organic matter. The humus itself is slowly decomposed into carbon dioxide, water, and simple salts.

There are several methods of counting soil bacteria, none of which gives absolute values. The direct smear and the ratio methods show the dead as well as the living bacteria and are subject to great error. The culture-plate method shows only those that are living and that will grow upon the particular nutrient medium used, which repre-
sents only a portion of the total. Lastly, the dilution method serves fairly well in counting some of the less numerous kinds of bacteria.

Efforts to correlate numbers of live bacteria with soil fertility have usually failed. Food supply, moisture, temperature, physical condition, and reaction of the soil all influence the numbers. The plowing under of green manures or other easily decomposable material will greatly increase the bacteria if other conditions are favorable (368). Fantastic numbers, running into billions to the gram, may be obtained by culture from such a decomposing mass (445). Similar figures obtained by microscopic methods (direct and ratio types) are reported from ordinary soil and have sometimes been interpreted to mean that only a small percentage of the organisms actually present are capable of developing in culture (408). The actual populations are no doubt much greater than the number shown by the plate count but vastly less than that obtained by the microscopic count.

Although particular individual bacteria may survive for long periods under special conditions, the ordinary bacterial generations are commonly very short. The numbers of bacteria present in any situation are continually changed by the death of myriads of organisms and their replacement by others. Billions of dead organisms accumulate in every gram of soil. So enormous is the total that protein (N × 6.25) determined in the usual soil analysis is largely composed of microbial remains.

The most numerous bacteria found in good arable soil are those that are able to use a wide variety of food materials. They break down complex organic substances to simple compounds, carbon dioxide, and ammonia. Certain bacteria initiate the process and others complete it, except where the nature of the material is such as to resist attack. The majority of soil bacteria are aerobes—that is, they must have air (oxygen) for growth. In many cases, however, very small amounts will suffice. A large group of such bacteria are active in the decomposition of organic matter. Some of them deplete the soil air of oxygen and then obtain a further supply from nitrates if these are present, reducing the nitrates to ammonia or to nitrogen gas. This process (denitrification) occurs especially in waterlogged soil where food is available and free oxygen is scarce. In ordinary field soils there is usually enough oxygen present so that little if any reduction of nitrates occurs.

The great bulk of the decomposition of organic materials in soils is carried on by aerobic organisms. But there are other bacteria, the anaerobes, which will not grow in the presence of oxygen. They occur in all soils but are probably dormant under usual field conditions, becoming important only in certain situations. Their action in breaking down organic matter is relatively slower and less complete than that of the aerobes and leads to an accumulation of ill-smelling compounds. One has only to dig in a peat bog to get the results of this anaerobic type of fermentation. Where the water table is permanently within 4 to 6 inches of the surface, a strong odor of hydrogen sulphide is reached within 10 to 12 inches. Under waterlogged conditions, oxygen is quickly exhausted, and the special type of decomposition releases the hydrogen sulphide. Plant materials
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growing at the surface successively die, partially decompose, and gradually sink. By the time they have fallen below the water level, the easily decomposed starches, sugars, and proteins are mostly gone, but the cell-wall materials, celluloses and related carbohydrates, lignin, and other resistant substances, seem to be preserved for ages. The history of bogs has been reconstructed by identifying the species of plants represented by the pollen grains whose walls have resisted decomposition for hundreds of years.

VARIous KINDS OF BACTERIA

In the break-down of organic matter, most of the carbon dioxide escapes from the soil into the air. The ammonia, on the other hand, is actively absorbed by the soil, and usually very little is lost. The odor of ammonia normally associated with a decomposing pile of manure or grass clippings disappears when a thin layer of soil is spread over the heap because the soil absorbs the ammonia and at the same time acts as a blanket to keep out oxygen, thus slowing up the rate of decomposition.

Ammonia absorbed by the soil is rapidly changed to nitrite and this to nitrate by nitrifying bacteria, which seem to be most active in the absence of organic matter, particularly in the laboratory, where they are very difficult to grow in pure cultures. Crude cultures of certain nitrite bacteria can be obtained by trickling a mineral solution containing ammonia through a tower filled with broken limestone which has a little soil scattered over the top. The use of a nitrite solution instead of ammonia will give a good development of the nitrate bacteria.

There are a number of forms of free-living bacteria that can fix nitrogen, several of which are widely distributed. Of these, Beijerinck described Azotobacter from soil in 1901 as a genus of micro-organisms that can use the nitrogen of the air in building up proteins within their bodies and thus by continued growth and death can increase the nitrogen content of the soil. This fixation of nitrogen can take place only in a neutral or alkaline soil. Acidity (pH values less than 6.0) apparently paralyzes the mechanism of nitrogen fixation. The bacteria can, however, remain alive in a soil more acid than pH 6.0, even though they fix no nitrogen.

Azotobacter has been found in certain soils all over the world, but in relatively small numbers varying from a few hundred to a few thousand per gram of soil. There is some question as to the importance of this bacterium to soil fertility because of the small numbers. Up to 40 pounds increase in nitrogen per acre per year has been attributed to Azotobacter by some workers, but others have become skeptical of its ability to give these results under field conditions. In the laboratory, in the presence of plenty of carbohydrate and the absence of much nitrogen, it is very easy to obtain an increase in the nitrogen content of cultures that contain billions of organisms. Further investigations will be necessary before the discrepancies between the laboratory results and the small numbers in the field can be interpreted.

Nevertheless the importance given to Azotobacter in the literature has led to the proposal to use it for determining the fertilizer needs of soil by the use of soil plaques. Unfortunately, the successes of this
method are restricted to special soils and conditions and hence it has no general application. Other micro-organisms, especially Aspergilus niger and Cunninghamella, have been proposed for similar determinations. When properly calibrated against field or greenhouse tests, they may be used to compare the fertilizer needs of particular fields of related soil types.

Early Roman observers recognized the value to the soil of growing legumes and exhorted the farmers to plant more of them. But it was not until 1886 that the reason for the beneficial effect of legumes was discovered. Since then the literature on this subject has become so extensive that a whole volume is needed to cover it adequately (116).

Briefly, the beneficial effect of legumes is due to the nodules on their roots. These are caused by bacteria that penetrate the rootlets and stimulate the plant to produce a growth at that point. The bacteria grow and reproduce inside this nodule, getting their carbohydrate and mineral food from the plant and their nitrogen from the air to form proteins that are released to the plant. Legumes, therefore, are able to grow normally in soil poor in nitrogen, provided other conditions such as soil reaction and available minerals are favorable.

The nodule organisms themselves have been found to belong to several groups, each of which is capable of producing nodules upon a series of leguminous plants. Within these groups there now appear to be special strains of nodule organisms peculiarly efficient upon particular legumes. The proper artificial culture can be grown in the laboratory and applied to the seed at planting time. By this means inoculation by efficient bacteria is assured, whereas if the inoculation is left to nature the rootlets might be invaded by a less efficient organism.

The amount of nitrogen fixed by legumes and added to the soil if they are plowed under varies greatly, depending upon the plant, the mineral and nitrogen content and reaction of the soil, and the season. Fifty to one hundred and fifty pounds of nitrogen per acre per year are fixed under average conditions. Under special conditions even greater gains may be obtained.

**ACTINOMYCETES**

As compared with that of the bacteria, not much is known of the physiology of the actinomycetes in soil. They are next to the bacteria in numbers, ranging from hundreds of thousands to a few millions per gram of soil. In size they are not much larger than the average bacterium. Many of them resemble molds in their manner of growth and in physiology. They are able to grow in drier situations and in deeper layers of the soil and they require less nitrogen than the bacteria. In field soils, they are most abundant in old sod and hence are probably associated with the decomposition of the grass roots. Great numbers may also occur in compost piles.

As a rule actinomycetes may be said to be decomposers of organic matter, attacking the celluloses and perhaps the more resistant soil humus. In this capacity they are important from the fertility standpoint in that they may set bound nitrogen free as ammonia. While certain species are pathogenic (that is, attack living plants and animals, producing disease), most of them are saprophytic (feed on dead material).
FUNGI

Associated with bacteria and actinomycetes in the rotting of plant remains are the fungi. Some of them are parasitic and begin the task of disintegration while plants are still growing; others attack dead plants only. Both are carried down with dead vegetation upon the surface of the soil or follow the root systems in its upper strata. Still others carry on their whole vegetative lives below the surface and only come to the surface to set free their spores. These species dot the meadows and pastures with mushrooms and puffballs and crowd the forest floor with varicolored fleshy bodies of Boletus, Collybia, Tricholoma, Russula, Lactarius, Amanita, the fantastic coral fungus (Clavaria), the slime molds, the cup fungi in their multitude of forms, and those microscopic molds whose beauty escapes detection until it is revealed by the compound microscope or studied in cultures.

Among these molds are many curious forms especially adapted to restricted conditions, but more important by far are cosmopolitan genera present in soils everywhere and participating in the decomposition of organic material. Common examples of these are species of Alternaria, Cladosporium, Mucor, Rhizopus, Zygorrhynchus, Penicillium, Aspergillus, and Trichoderma. Everywhere dark-walled forms, species of Cladosporium, Alternaria, Helminthosporium, and similar genera cover the surfaces of vegetation in the fall and winter after the first frost and give it the gray, dirty, or weathered look so familiar in the garden and fence corner.

Among such fungi many species are harmless saprophytes; others are able to attack roots of crop plants as well as to live independently in the soil; still others are parasites that cannot live in the absence of host plants. Under natural conditions of competition the effects of the destructive types are only occasionally seen. Under cultivation, however, the conditions of growth found in nature are disturbed, and native or introduced species of fungi frequently become epidemic. In certain regions of the Southwest, the root disease caused by Phymatotrichum, a native fungus, has become enormously destructive. While the greatest damage has been done in the cottonfield, shade trees, vegetables, and ornamentals are not spared. Similarly, wilt diseases affect cotton, flax, watermelon, and many other cultivated crops. The fungi involved are forms that take advantage of the new conditions and multiply until sometimes whole areas are so badly infected that crop production is no longer profitable.

MYCORRHIZA

Close association of fungi with the roots of green plants occurs conspicuously in the forest. The feeding rootlets of the forest trees turn upward from main roots and penetrate the surface layers of soil and decaying litter as a fine network. In such situations the ultimate tips or the annual series of feeding rootlets of many species are covered with mantles, or closely woven masses of mold hyphae. In other species the mold threads penetrate between the cells of the outer layers of the root cortex. This association appears to serve as one means of breaking down plant food by fungous action so that it can be absorbed directly by the plant. Such mycorrhiza takes many forms and occurs on annual
plants as well as on trees. The fact that such relations occur and that both organisms have adjusted themselves to a sort of communal life is well established, although the extent of interdependence between fungus and green plant is a matter of controversy.

**PROTOZOA AND MYXOMYCETES**

In this population of millions of organisms to the gram, the one-celled animals, protozoa, constantly appear, primarily as destroyers that prey on bacteria. They are mostly free swimming and are dependent upon free water for activity. Certain of the smaller species have been found to be represented in soils of widely differing physical and chemical composition and under most varied climatic conditions (336). The larger ciliated forms are only found under excessively wet conditions in highly fertilized soil or in loose-textured swamp areas.

On account of their activity in feeding upon other organisms, the protozoa have been regarded as a factor in maintaining microbiological balances. Bacterial populations seem to be reduced by them in some soils but are not affected in others.

The slime molds form a group of micro-organisms that has been often overlooked. These myxomycètes seem to be intermediate in their characteristics between the protozoa and the fungi. They flood the surface layers of moist soil rich in organic matter with colonies of individuals that prey upon the smaller forms, such as bacteria, actinomycetes, and molds. After their feeding season is finished they come together in great aggregates of individuals or fuse into jellylike masses that ultimately come to the surface and produce their spores in variously formed, often very beautiful structures.

They too are considered significant as a factor in maintaining a balance in soil population.

**WORMS AND BURROWING ANIMALS**

Worms varying in size from great earthworms to forms scarcely visible to the naked eye are represented in the fauna of most soils. The smaller forms are seen mostly near the surface in the A horizon. The well-known earthworms feed at or near the surface upon plant remains, which are ingested or dragged into their burrows. These species are so dependent upon moisture, however, that they must encyst or withdraw into the deeper layers of the soil in dry weather to keep their bodies moist. Since they drown in water, the larger species are found inhabiting permanent burrows, often running vertically several feet, which make possible a safe balance between air and moisture requirements. Large amounts of earth are ingested with their food and pass through their alimentary canals. Their casts, which consist of earthy matter bound together with the humidified residues of food eaten, furnish a suitable environment for many micro-organisms. Marbut expressed the belief that in certain areas the granular condition characterizing whole layers of soil was due to earthworm casts. Certain mulls, or granular mixtures of mineral and organic material produced by earthworms, give particular areas of the forest floor their whole character.

The larger animals that burrow into the earth for protection or in search of food play a secondary part. Their holes or burrows form
open channels which carry air and rain water into the deeper layers, increasing the absorbing power of the soil. Where they form complex networks, such as may be readily observed in the forest or in grasslands, these burrows are capable of impounding great quantities of rain water which might otherwise run away. Sometimes they also form the starting point where streams of water begin the break-down of banks and hillsides, resulting in the ruin of large areas of soil.

**BALANCED MICROBIAL POPULATIONS**

In virgin soil or in areas in which natural competition has been undisturbed for long periods, the micro-organisms and green plants are found to reach a fairly stable balance. The swamp, the forest, the prairie, change their aspects slowly over long periods. When farming operations are introduced, this balance is destroyed. Whole sections of the organic population are wiped out, and new alignments are started. Plowing and cultivating increase the activities of the micro-organisms, and the accumulated organic remains that made the freshly broken prairie so fertile are broken down at a greatly accelerated rate. In many areas no adequate steps have been taken to replace what has been destroyed. Micro-organic activities in the soil are desirable when they serve man’s purpose; they become undesirable when they are stimulated to the point where they destroy fertility faster than it can be replaced.

Studies of the microbial population of the soil have thus far been mainly descriptive—totals have been enumerated; particular species have been isolated and studied in the laboratory; specific treatments have been applied; and effects upon total organisms have been determined. Constructive experimentation is required to determine just what microbial activities are needed for particular crops in each soil group and how those activities may be maintained at desirable levels.

Correspondingly, the existence of unfavorable microbial activities in many soils is already known. Much experimentation will be necessary to establish means of elimination, of control, or of replacement of undesirable by desirable species.