THE SOIL AND ITS FERTILITY

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Preface

Soil, though of tremendous importance to all men, is little understood by most, including even those who gain their livelihood directly from it. Many books have been written about soils, but a new approach to the subject appeared desirable, and this has been attempted here.

The aim of the authors has been to describe the soil, its constituents, properties, and actions, in intimate relation to the plants which it produces, while explaining what renders a soil fertile and a fertile soil productive. To follow all the reasoning, a fundamental knowledge of chemistry and biology is required, but the lay reader may skip the chemical formulas and other highly technical paragraphs without losing the thread of understanding. In other words, the scientific details given may be taken on trust, but they had to be included to leave no doubt about basic facts and to make it possible for anyone to check up for himself.

The text endeavors to develop the theme in logical sequence from the simple to the complex, so that the reader should find understanding of the entire subject most easy when he starts at the beginning. Parts I, II, and III, especially, should be read in their proper sequence. The seven parts of the book have been given the greatest possible independence, however, because of their varying importance for immediate practical application. In order to assist those who pick out certain chapters for separate reading, frequent references are made to other pages where certain facts have been explained in detail. The nonscientific reader may familiarize himself with the meaning and application of the terms and expressions generally used in similar literature by referring to the glossary.

More efficient crop production and more successful soil conservation require greater knowledge of soil science. If this book contributes to the production of better crops and to the easing of food shortages throughout the world, the authors will feel amply repaid.

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Montreal, P. Q.
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INTRODUCTION

The soil of the earth is "the great provider," the storehouse of nature, furnishing, as it does, the sustenance of all plants, animals, and men.

For uncounted geological periods soil has served in this manner, long even before man appeared on the scene. Vast numbers of plants and animals—some of giant size—and finally men populated the earth, and the soil supported them all, entirely without human assistance. Now, especially during the last few decades, ever-repeated and ever-more-urgent warnings are heard that the soil is giving out or at least requires more careful attention, that more food is urgently needed, and that millions suffer from hunger. What are the reasons for this state of affairs? They are manifold, and it is erroneous to assume that the present state of world-wide unrest alone should be blamed. Unrest affects mainly distribution; it is the supply which must be considered. No doubt remains that in many parts of the world the supply of foodstuffs is reaching dangerously narrow and ever-diminishing margins of safe surplus.

That living standards have risen throughout most of the world and that the simple and nourishing—though often monotonous—foods which once sufficed are no longer generally acceptable cannot be denied. It is also true that large quantities of food are wasted in the effort to please finicky appetites. These, however, are no more than minor contributing factors to the increasing food shortage.

The most important reason is the enormous and rapidly progressing increase in world population, amounting to about 500 million additional food consumers since the beginning of this century. This increase is due largely to progress in medical science and the resultant improvement in sanitation. Because of wider knowledge and more intelligent care, through the employment of almost miraculously effective preventive and curative medicines, and by means of advanced methods of surgery, untold numbers of lives are being saved which formerly would have been lost. Infant mortality as well as the death rate of mothers in childbirth has been lowered to an astonishing degree, while, at the same time, the life expectancy of adults has been raised considerably. These are great blessings to mankind, but it is often overlooked that they impose an equally great obligation. This obligation concerns the soil which has to feed and sustain the increasing millions of humanity.

What are our soil resources? Of the approximately 37 billion acres of total land area of the world, some 30 per cent is climatically suited for food production. Only a variously estimated 10 per cent (or even only 4 per cent, excluding hay fallow) is actually so used. Naturally, the 10 per cent which is now under cultivation includes not only most of the best-suited but also the most readily accessible areas. It is evident, even from these merely approximate figures, however, that there is still considerable room for expansion. Through work and knowledge, man may well be able to refute the various prophets of doom who, of late, have been loud with proclamations that mankind is headed toward starvation because of overmultiplication of the human race.

Application of knowledge is needed, for instance, in farming practices which, even in the agriculturally most highly developed countries, are still capable of considerable improvement and intensification. A better understanding and more intelligent treatment of the soil, fearfully abused in the past, must be the first step.

It is sad, indeed, to contemplate the wide areas of formerly productive soil in various parts of the world which have been turned into near-deserts through ruthless exploitation and wrong methods of culture. Untold millions of tons of invaluable fertile topsoil have been lost in this manner through water and wind erosion, and other areas have been so impoverished that it simply is not worth while to try to raise crops on them.

All of these areas can be, and eventually probably will have to be, reclaimed, but to accomplish this is slow, tedious, and expensive work. In the meantime, these areas are temporarily lost to production. How much better would it have been never to have lost them at all! The question arises, how can soil be maintained in fertile condition in spite of the fact that crops are continuously harvested from it?

Under natural conditions a balance is established under which the soil carries as much—and not more—plant growth as it can nourish. Its nutrient resources are being maintained at a fairly permanent level through the gradual return of nearly all of the organic matter into which the various nutrient elements have been transformed by the growing plants and animals. If the supply of any of the critical elements becomes low, the macro- and microflora and fauna adjust themselves in a slow cyclic change, so that actual exhaustion of the soil does not take place.

When soil is used by man for the growing of crops, a large part of the organic matter is removed in harvesting, and cultivation of the soil causes some of the elements to form new chemical combinations in which they may no longer be as readily available to plants. This results in the soil becoming poorer and poorer, the longer it is used. The main reason is that all of the nutrient elements can be utilized by plants, men, or animals only in certain strictly circumscribed combinations or compounds, and that these latter definitely are exhaustible. In cultivated soils they must, therefore, be continuously replenished, and their natural re-formation in the soil must be furthered and encouraged through proper soil treatment.

This principle, though it is so frequently sinned against, is by no means a recent discovery. The Chinese practiced soil conservation, long before the Christian Era, by adding manure as well as wood ashes and the composts of plant refuse to the soil of their fields. In ancient Rome and in other countries of antiquity, the application of animal and human manure as fertilizer was frequently regulated by law. Homer, in his famous "Odyssey," mentions the use of stable manure for agricultural purposes, and the great historian of antiquity, Xenophon, gives definite directions as to how stable manure should be mixed with plant refuse in order to produce a rich and fertile compost.

Though these ancient people did not know the reasons underlying the effects of natural fertilizers, they had undoubtedly observed that excrements of animals produced greater soil fertility in the spots where they happened to be dropped. Many ancient scripts make mention of the fact that manure which accumulated in places where domesticated animals were penned up for the night was later spread evenly over the fields.

Green manuring (the plowing under of green plants to increase soil fertility) was likewise well known and widely practiced in various parts of the world long before the Christian Era.

An important step forward in the understanding of plant nutrition was initiated by the discoveries of Justus von Liebig, who in 1840 advanced a new theory based on a large number of analytical investigations of the ashes of plants from which he determined their mineral contents. Von Liebig explained and demonstrated that the inorganic elements which the plants had extracted from the soil could be replaced in the shape of artificially produced inorganic fertilizers, and that in this manner the fertility of the soil could be maintained or even increased. In his classical work "Die Chemie und ihre Anwendung auf Agrikultur und Physiologie" ("Chemistry and its Application in Agriculture and Physiology") he mentions also that stable manure and compost, by themselves, are not sufficient to restore complete soil fertility. He insists that certain inorganic compounds which are readily assimilable by plants, in particular certain ones containing phosphorus and potash, must likewise be incorporated in the soil. He describes, in the main, the very same procedures which today are generally accepted and applied, and which consist in the chemical decomposition of natural and artificial phosphates, through the action of sulfuric acid, as well as in the application of readily soluble compounds of potash.

Liebig's ideas were accepted with particular enthusiasm in England, where such men as Flemming, Proctor, Ryland, Muspratt, and others established commercial enterprises for the wholesale manufacture of such "artificial fertilizers" from bone meal and mineral phosphates. Great advances have been made since then, and the vast extent of the modern fertilizer industry in all countries is common knowledge.

It may be of interest to trace at least a few of the steps which have led to the present state of understanding of this matter. In 1842, two years after the appearance of Liebig's fundamental work, the English farmer John Bennet Lawes was awarded his now historically famous patent No. 9353 for an "artificial fertilizer" which he had invented, and which he had tested on his farm in combination and in comparison with various other fertilizers. In cooperation with Sir J. H. Gilbert, Lawes continued his experiments relating to the maintenance and increase of soil fertility for nearly half a century. One year before his death he dedicated and deeded the farm, on which all his work had been carried out, to the services of humanity. The experimental station, which, with the assistance of various scientific institutes was established on this farm, and the agricultural experiments which have been carried out there now for over a century, have made the name Rothamsted, a nearby manor at Harpenden, Herts, England, known and famous all over the world.

The oldest experimental field in the United States is at Urbana, Illinois, where, in 1876, G. H. Morrow commenced systematic investigation of the result of soil treatments in relation to crops. He proved that considerable increases in yields could be produced through correct soil management.

Similar and numerous agricultural experiment stations now exist in nearly all countries of the world. Usually, they are government maintained, which signifies that their great importance for the well-being of the population is fully recognized. One of their main activities, besides the breeding and testing of improved plant varieties, is the scientific study of the soil—its fertility, its productiveness, and the means by which it may be maintained in the best condition. The results of these investigations are then made available to the practical farmers and plant growers, so that they may improve their methods.

Many excellent, instructive, and helpful pamphlets, which may be obtained from these stations on request and without charge, are at the disposal of all who wish to make use of the information they contain. By necessity, however, these pamphlets usually are limited in scope, and, in most instances, they confine themselves simply to giving directions on how one must proceed in order to obtain certain well-defined results.

The claim is justified, however, that the farmer and gardener will be in a much better position to practice what science teaches if he is told not only *how* he should proceed but if he understands at the same time *why* the variously recommended measures are likely to lead to success. This remark is not meant to imply a criticism of the above-mentioned pamphlets, which would become too voluminous and repetitious if detailed explanations of the underlying reasons were included. Besides, there is a vast amount of literature on the composition and the proper treatment of soils contained in voluminous handbooks as well as in numerous scientific journals, and in these the *why* of the matter is usually set forth very clearly. Unfortunately, the practical farmer and gardener usually does not have access to these publications and, if he manages to obtain them, he is likely to find them too technical for easy understanding.

Facts which are only partly understood or misunderstood, however, are likely to lead to odd notions, fads, and fancies, and frequently result in practices which may do considerable harm. Such is human nature. The focus of the most heated discussion is on the choice of the "correct" type of fertilizer.

One faction considers the application of artificial fertilizers as the most important requisite for high crop yields, since this offers a ready means of replacing the nutrients, in particular nitrogen, phosphorus, and potassium, which have been removed from the soil with the crop. That this reasoning is correct in principle has been proved beyond doubt through the doubling and tripling of yields in many countries since the advent of artificial fertilizers.

The opposing faction considers the application of artificially produced chemicals to soil not only as unnecessary but even harmful, and it bases its whole faith on so-called natural fertilizers, such as stable manure, compost, and green manure. Its shibboleth, frequently preached with fanatical ardor, is a sort of "return to nature."

There is no need of going into details here on these opposing claims, since it will be explained later on in this text where both factions are right and where they are wrong. It will be shown that high production can be reached and soil fertility maintained most readily if both natural and artificial fertilizers are used, with careful control of their proportions by frequent determination, through analysis, of the soil's needs. To know at all times the actual needs of the soil is more than half the battle won.

PART I

The Composition and Contents of the Soil

1. THE ORIGIN AND FORMATION OF FERTILE SOIL

That soil is vastly complex, that it is, in fact, the most complex substance on the face of the earth, is the first truth to be understood in a study of the soil. This becomes readily evident when one considers how soil came to be what it is.

Decomposed Rocks

Soil consists, first of all, of decomposed rocks—all the different types of rock on earth containing all the minerals known to occur on earth. Decomposition of rock results from the simultaneous action of several vital forces which can be grouped into mechanical forces—such as action of water, changes of temperature, and grinding by ice—and chemical forces, consisting of chemical reactions of one mineral substance with another. The combined action of these forces causes not only progressive breakdown but also the formation of completely new substances not originally present in the rocks. It is in this manner, for instance, through a series of complex chemical processes, that clay is produced, and it need not be emphasized that clay is one of the most important components of a fertile soil. The fact that during this very same series of reactions such minerals as potassium, manganese, calcium, magnesium, and iron are freed from the rocks and converted into soluble salts leaves no doubt about the importance of these forces of decomposition.

Decomposed Organic Matter, Humus

Higher plants cannot as yet live on the above-described purely mineral mixture, because one vital component is still missing. This is organic matter, more commonly known as *humus,* which is required by most of the important soil microorganisms as a source of energy, besides fulfilling various other important functions, as described in Chapter 3.

Derived in the beginning from dead bacteria and algae, humus gave first water plants and then land plants their chance for a start. Even at present, algae and bacteria, and after them mosses and lichens, are the first humus formers in a mineral soil, preparing the way for higher plants. The terms *humus* and *organic matter,* however, cover a vast variety of substances, derived from the dead and decomposed bodies of all kinds of animals, as well as from the remains of dead plants, including huge trees, minute algae, and anything in between. This description indicates that a soil containing organic matter may include, besides any known type of mineral, just about any kind of organic compound known to occur on earth.

Complexity of Soil Mixture

When one now considers the results of volcanic upheavals, which during the formative period were common all over the earth, covering vast areas with volcanic ash, as well as the combined action of water, wind, and ice which over eons of time have ground, shifted, and mixed all of this soil material, often transporting it for hundreds or even thousands of miles and depositing it wherever chance permitted, one has an explanation for the great variety of soils, differing in composition and behavior, which may be encountered in various places. Climatic conditions, often entirely local in effect, contributed still further to differentiation. It is evident that the further development of a soil depends also on whether it became covered with forest or with prairie grasses for perhaps thousands of years, whether the water table was high or low, or whether rainfall was abundant or scanty.

Classification of Soils

As explained in Chapter 16, the great number of different soil types have been classified and are platted on soil maps, though these latter can never be more than a preliminary aid for the practical farmer and gardener. As should be rather clear from the foregoing, different types can be defined clearly only in large groups, and, the smaller the subdivisions become, the less well defined can they be, since these unavoidably merge into each other.

The fundamental distinction should be made between mineral soils and organic soils, depending upon the proportion of organic matter which they contain. A clear and sharp division between these two types, however, cannot be expected either, and gradual transitions from one type to the other are generally found wherever soil supports plant growth. In general, a soil is designated as *organic* when it contains 20 per cent or more of organic matter.

A study of soil—what it is and how it acts—must by necessity commence with a survey of individual contents, and, since in evolutionary sequence the soil minerals had to be present before plants and animals and, therewith, humus could develop, the mineral soil constituents will be considered first.

2. THE MINERAL SOIL CONSTITUENTS

ELEMENTS REQUIRED IN PLANT NUTRITION

Some 64 elements have been identified as being contained in the tissues of living plants, though the presence of about half of them appears to be merely incidental; at least, so far, it has not been possible to assign a useful function to more than 25 or possibly 30 of these elements, as far as plant life is concerned. This does not necessarily mean that all the others are definitely and entirely superfluous. The importance of some of those elements which now are considered to be required nutrients has been only recently discovered, and it is possible that more will eventually be added to the list.

Elements of Prime Importance

According to the present state of scientific knowledge, the following 14 elements must be considered as of prime importance, because they are absorbed by plants in relatively large amounts: carbon, oxygen, hydrogen, nitrogen, phosphorus, potassium, sulfur, calcium, magnesium, iron, silicon, aluminum, chlorine, and sodium. Likewise known to be required for healthy plant development, though absorbed by plants only in very small amounts, are the following 7 elements: boron, manganese, copper, zinc, molybdenum, cobalt, and probably vanadium. Very commonly contained in plant tissues, though usually only as minute traces, are: uranium, radium, thorium, actinium, iodine, cesium, barium, strontium, lithium, chromium, nickel, arsenic, fluorine, and selenium.

The following is meant to serve merely as a general survey, pointing out the nature and significance of the various elements. Their actions in the soil and the factors which control their availability to plants are described in Parts III and IV.

Carbon. Carbon is always available in ample amounts, since plants are endowed with the ability to assimilate through their leaves the carbon dioxide of the air. As is explained later (see photosynthesis, page 100), the plant leaves use only the carbon fraction of the carbon dioxide, and the freed oxygen is returned to the air. The properties and actions of carbon are detailed in Chapter 24.

Oxygen. Most of the oxygen which is utilized by plants enters by way of the roots in the soil water, though a certain amount is taken also from the air.

Hydrogen. Hydrogen, which, like carbon, is required in photosynthesis to produce carbohydrates (especially sugar and starch), is acquired by the plants directly from the soil water (H_2O) which, as the formula shows, is a compound of oxygen and hydrogen.

Nitrogen, Phosphorus, and Potassium. Nitrogen, phosphorus, and potassium occupy a rather unique position as far as soil fertility is concerned. These are the "big three" of plant nutrition, or, as they also have been designated, "the trio NPK" (derived from their chemical symbols). Since natural production of the soluble compounds—the only form in which these elements are available to plants—proceeds in the soil rather slowly, and since growing plants absorb them in comparatively large amounts, they are highly exhaustible. Their annual removal with the harvested crops is, therefore, a matter of much more serious concern than is true of most other elements. In fact, when nitrogen, phosphorus, and potassium are not replaced regularly through the application of fertilizers, either artificial or natural, a lack of these indispensable elements will show itself sooner or later in the growth of the plants. For this reason these critical elements are treated in considerable detail in later chapters. (See Chapters 18, 19, and 20 and Part V.)

Sulfur. Sulfur, which appears to be involved in the nitrogen metabolism of plants, has long been known to be essential for healthy plant development. Most soils contain it in sufficient amounts, and, in addition, it is a component of many commonly employed fertilizers which serve to replenish the supply. In certain regions, however, for instance on the Atlantic and Gulf coasts of North America as well as on the coasts of northern Europe, soils deficient in sulfur do exist; application of sulfur under such conditions has produced marked increases in crop yields. From numerous investigations it appears that sulfur serves mainly as an agent in making other nutrients more readily assimilable, though it also seems to have a direct effect on plant metabolism, exerting an influence on the type of carbohydrates and proteins which are formed. Since this element, furthermore, has a pronouncedly favorable influence on the healthy development of nitrogen-fixing bacteria—as well as of other soil microorganisms—it is not surprising that sulfur applications are frequently found to be very beneficial in the culture of various legumes, such as alfalfa. That overabundance of sulfur—which may develop when sulfur is applied repeatedly to an already somewhat acid soil—may have toxic effects must not be overlooked. General application of sulfur as fertilizer, without previous soil analysis, is not advisable. (For further details, see Chapter 22.)

Calcium. Calcium is of considerable importance in plant nutrition and is a required nutrient. Since its availability depends upon many other factors, however, which are discussed in Chapter 21, and since liming procedures and liming effects are explained in Part VII, no further details need be given here.

Magnesium. Magnesium has long been known to be indispensable for the development of the green coloring matter of the leaves (chlorophyll), but its actual role in this complex process has been revealed only recently.[1] Evidently, magnesium is prominently involved in the production of adenosine triphosphate (see photosynthesis, page 102) as well as of other polyphosphates which are essential for many enzymatic syntheses within the plant. (See enzymes, page 79.) In nature, magnesium is nearly always associated with calcium, and, for this reason, is commonly present in soils. It is added incidentally when lime is applied in the form of powdered limestone (especially dolomitic limestone, sometimes called *horticultural limestone*). Deficiency, however, is by no means as rare as might be expected. Especially in very sandy soils, and in particular in the culture of tobacco, potatoes, and other plants with ample leaf development, a lack of magnesium has been observed quite frequently. Such a deficiency is revealed by a yellow discoloration of the leaves, caused by a lack of chlorophyll and termed *chlorosis*. The minimum soil level of magnesium content, below which deficiency symptoms are likely to appear, is 25 lb/acre. A magnesium level of approximately 100 lb/acre is considered to be most generally favorable. Experiments carried out in various parts of North America, as well as elsewhere, with many different types of soil have shown that many other kinds of crop plants, besides the two mentioned above, are measurably benefited by application of readily available magnesium. (See page 317.)

Iron. The importance of iron for plant nutrition is thoroughly established, but it is not as commonly recognized by the practical farmer and gardener as it deserves to be. Most soils contain sufficient amounts of this element, but in cultivated soils it is easily converted into unavailable forms or is leached away. In addition, physiological interference by other elements, especially calcium, may prevent plants from moving sufficient amounts of iron to their leaves, so that iron-deficiency symptoms appear

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[1] Ingraham, L. L. and Green, D. E., *Science*, **128**, 310 (1958).

in spite of the fact that sufficient iron in available form is present in the soil. The conversion of iron from one form to another and its interaction with other elements, which has a vital influence on plant growth in general, are treated in considerable detail in Chapter 23. (See also page 318.)

Silicon. Silicon is contained in the stems or leaves of all plants as well as in the husks or shells of fruits. In the grasses, such as the cereals or sugar cane, and others, it supplies structural strength. It has been suggested that silicic acid in colloidal form facilitates, in some as yet unexplained manner, the assimilation of other elements by plants. Though this is well within the range of possibility, no definite proof of such action has so far been obtained. Since silicon is one of the most common and most abundant of all elements, however, forming, as it does, the chief constituent of the earth's crust, it is always present in ample amounts, and its addition to the soil for fertilizer purposes need not be considered.

Aluminum. Aluminum is a component of all types of clay (argillaceous earth), and is almost omnipresent in all soils. Though this element has been found quite generally in all plant ashes, being present in fairly large amounts especially in green leaves and in flowers, it is not certain, as yet, whether aluminum actually is required as a plant nutrient. That still more is to be learned about the importance of aluminum is indicated by a report which tends to show that the presence of aluminum in nontoxic quantities contributed measurably to the healthy development of orange and other citrus trees. Otherwise, little is known about this element except that it appears to influence the flower color of certain plants, of which the hydrangea ("four season") is best known. A surplus of available aluminum in the soil is harmful to plants and may cause serious damage. Active aluminum frequently is the main detrimental factor in crop production on acid soils. This fact should be borne in mind, especially when aluminum sulfate is added to soil in order to increase its acidity. (See pages 234 and 416.)

Chlorine. Chlorine, present in nearly all soils in the form of chlorides, shows much similarity to sulfur in its effect on plant life. In the first place, it is equally common in its distribution, and soil is rarely deficient in it. Chlorine also is precipitated from the air by rain and snow and is contained as chloride in various fertilizers. Its role in plant nutrition is not perfectly clear, but it appears to have an influence similar to that of sulfur, i.e., assisting in the absorption of other important elements, provided that it is not present in large, and therefore toxic, amounts. Experiments tend to show, furthermore, that chlorides exert a favorable influence on the water economy of plants. It has been found that during dry seasons chloride fertilizers give results superior to sulfate fertilizers, whereas the latter were more effective when the precipitation rate was high. It also appears that there is a definite linkage between the assimilation of chloride and nitrogen. Systematic experimentation[2] established that chloride fertilizers affect the protein metabolism of plants favorably in the presence of nitrate (NO_3) and unfavorably in the presence of ammonia (NH_4). This interaction is so pronounced and reliable that application of nitrate can be recommended as a remedy for chloride injury. Soil deficiency in chlorides is so rare that it is of little importance.

Sodium. Sodium is very much misunderstood and is frequently even considered to be generally toxic to plants. Actually, it becomes toxic only in fairly high concentrations, and small amounts have a distinctly beneficial effect on many crops. Responses to the application of sodium chloride (NaCl, common salt), however, are better with good drainage than with poor and in a wet season than a dry one. Investigation and experimentation[3] have shown that crops may be divided into four categories of sodium (Na) response:

(1) Little or none, even with insufficient potassium supply: cucumber, lettuce, onion, parsley, peppermint, spearmint, spinach, squash, strawberry.

(2) Slight to medium, even with insufficient potassium supply: asparagus, broccoli, sprouts, carrot, chicory, horse-radish, tomato.

(3) Slight to medium, even with ample potassium supply: cabbage, celeriac, kale, kohlrabi, pea, radish, rape.

(4) Large response, even with ample potassium supply: celery, Swiss chard, mangles, beets, turnips.

It appears that in those crops which were found most responsive to sodium, the latter assists in the function of potassium—not merely replacing it—and the sodium seems to be quite as much of a required nutrient as potassium.

Greenhouse experiments with cotton,[4] on the other hand, have shown rather clearly that, with this crop at least, sodium was able to replace potassium. The application of sodium chloride to sand cultures of cotton increased growth by an average of 53 per cent, as long as potassium was absent. The beneficial influence of the sodium remained noticeable only as long as the potassium (K_2O) content of the sand was less than 300 lb/acre and that of soil less than 72 lb/acre. The inference is that sodium is likely to act in a similar manner also with various other plants.

At any rate, it is certain that sodium cannot simply be considered as

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[2] Buchner, A., *Z. Pflanzenernähr. Düng. u. Bodenk.*, **55**, 124 (1951); **57**, 1 (1952).

[3] Harmer, P. M., and Benne, E. J., *J. Am. Soc. Agron.*, **33**, 952 (1941); *Soil Sci.*, **60**, 137 (1945); **76**, 1 (1953).

[4] Holt, M. E., and Volk, N. J., *J. Am. Soc. Agron.*, **37**, 821 (1945).

an undesirable soil constituent, except when it is present in such large amounts that it creates high alkalinity and interferes with the availability of other elements. That sodium is a very common constituent of plant ash suggests that this element fulfills a useful function in plant life. Unfortunately, it is still not possible to define clearly in each instance what this function is, since it appears to vary. Sodium should be applied only when soil analysis shows a definite lack and when the crop plant to be raised is known to be benefited by sodium.

Trace Elements

The seven elements which are to be discussed next are the most important ones of the so-called trace, minor, or rare elements. All—thougb now definitely known to be required by plants—are usually present in the soil as well as in the plants only in very small amounts, or traces, hence their designation. Actually, their importance is entirely out of proportion to the minute quantities which satisfy the needs of plants, and to overlook them is a grave error which may lead to damage or loss.

Boron. Boron, of which a great deal has been heard of late, occupies a rather singular position in plant life. On the one hand, it is indispensable in plant nutrition; on the other, it is never required in large amounts. Even a small surplus of this element in the soil may cause serious damage. This fact renders the correction of boron deficiency rather difficult. In at least one case, where an attempt was made to do so, the application of the small amount of 50 lb of borax/acre resulted in the death of potatoes and tobacco.

On the other hand, the same amount of borax per acre applied to an apple orchard, suffering from the deficiency disease called *internal cork of apples,* had extremely favorable results and produced complete control for over 3 years. Deficiency in boron causes various other symptoms, such as stem cracking of celery, heart rot or dry rot of beets and turnips, stunting and malformation of cauliflower heads, and partial breakdown of the leaf tissue of tobacco with resultant curling and distortion of the leaves. Certain crops, such as cucumbers, beans, and strawberries, are very sensitive to a slight overdose of boron and are easily injured, whereas beets, cauliflowers, and turnips are quite tolerant and are not injured by relatively heavy applications. Most other crops are intermediate between these extremes. The physical condition of the soil, the acidity, and the content of organic matter, as well as other factors, have a decisive influence on the toxic or nontoxic effect of a given boron concentration. Great caution, therefore, is advisable in the use of boron. (See page 320.) Fortunately, experiments have shown that boron toxicity, caused by overapplication, disappears from most soils after a period of 2 months.

Boron plays an important role in cell division and appears to be directly involved in various metabolic processes such as protein synthesis and carbohydrate metabolism.

Manganese. Manganese, which, according to recent findings, plays an important role in the synthesis of proteins within the plant and may have other functions as well, is unquestionably essential to plant growth. Most soils contain it in sufficient amounts, though it is likely to leach away from acid soils and to become available with more or less difficulty in alkaline soils. Physiological deficiency may occur in the same manner as with iron in the presence of surplus calcium and can be corrected through application of ammonium sulfate. (See page 246.) True manganese deficiency has been observed, especially in sandy soils, on tobacco, tomatoes, and soybeans, resulting in chlorosis (yellowing and spotting of the upper leaves). Organic soils, such as those used for celery culture, are quite frequently deficient in manganese, and under such conditions manganese deficiency may cause a decrease in yield without the appearance of deficiency symptoms. Unfortunately, as is the case with boron, a surplus of freely available manganese in the soil may likewise cause serious injury, and warning must be given never to apply manganese to the soil without previous careful analysis. Special caution must be practiced when applying manganese to a truly acid soil, because this element is highly soluble at low pH levels, and even a slight surplus may cause damage. (See page 318 for manganese application in case of deficiency.)

Copper. Copper compares with manganese and boron in that it is present in nearly all soils (in amounts between 1 and 100 ppm) and is contained in the ashes of most plants. It has been found in comparatively large amounts particularly in seeds, and carefully controlled experiments have shown that, without small amounts of copper, many plants actually are unable to produce seeds. Copper deficiency of pasture plants has been observed to result in lowered elasticity of the wool of sheep. Abnormalities in plant growth, for which copper deficiency was blamed, have been observed in particular on peat or muck soils, though deficiency appears to be not uncommon also in acid sandy soils. It has been reported that the application of 25 lb/acre of copper sulfate produced a definite improvement in the development of lettuce and various other plants which were being raised on peat soils in Florida and New York. The addition of copper to the average mineral soil is advisable or advantageous only under very special conditions and should be carried out only when analysis points to a definite deficiency. (See page 321.)

Zinc. Zinc is a very common component of plant tissue (in amounts varying from 1 to 50 ppm), and the fact is pretty well established that the presence and availability of this element is an important requirement for the satisfactory development of grain crops, beans, buckwheat, and other plants. Unfortunately, the correction of zinc deficiency is as difficult as is that of boron and manganese, since, like the other two, zinc is extremely toxic even in a very small overdose.

Careful experiments have shown that zinc appears to be required by plants for the maintenance of certain growth substances (auxins) and is involved in protein synthesis. Its lack results in various growth abnormalities. Zinc deficiency has been studied in particular on fruit trees such as apples, peach, cherry, pecan, and grapes, where it causes the so-called little leaf or rosette disease. On grapefruit and other citrus as well as on avocado, it causes mottle-leaf. Zinc sulfate-lime sprays, applied either to the leaves or to the soil, have been found to be most effective in correcting such a deficiency without causing injury. Dormant sprays of zinc sulfate are employed also. (See also page 321.)

Molybdenum. Various investigations[5] have supplied proof that molybdenum has a decisive influence on the efficiency with which plants absorb and utilize other elements, most of all nitrogen but possibly also iron and phosphorus. There is convincing evidence that molybdenum acts as a catalyst in the nitrogen fixation of the nodule bacteria of legumes as well as of free-living nitrogen-fixing bacteria, and that it plays an equally important role in the nitrogen assimilation of all higher plants. It appears that molybdenum is essential for the production of certain enzymes involved in the reduction of nitrate to ammonia within the plant. The formation of glutamine, one of the steps in protein production, also requires molybdenum.

It was further found that application of more than ½ lb/acre of molybdenum trioxide (MoO_3) to soils with a pH below 6, or more than ¼ lb/acre to soils with a pH above 6, is likely to raise the molybdenum content of hay to a point where it becomes toxic to cattle (10 ppm molybdenum content of dry plant material is sufficient to cause trouble). Ingestion of such hay by cattle causes tart disease, the main symptom of which is extreme diarrhea. In experiments carried out in Australia, where molybdenum deficiency was observed, application of 1/16 to 1 oz/

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[5] Mulder, E. G., "Plant and Soil," I, p. 94 (1948); Evans, H. J., Ph.D. thesis, New Brunswick, N.J., Rutgers University (1950). Also Nicholas, D. J. D., and Nason, A., *J. Biol. Chem.*, **207**, 353 (1954).

acre of molybdenum trioxide gave beneficial results with legumes, especially clover. Applied to the soil in the form of a spray, 1½ lb/acre of sodium molybdate ($Na_2MoO_4 \cdot 2H_2O$) has also been found effective in correcting molybdenum deficiency.

The whiptail disease of cauliflower is believed to be a symptom of molybdenum deficiency.

Cobalt. Cobalt is readily absorbed by plants, and it was discovered in New Zealand that a serious cobalt-deficiency disease (bush sickness) of sheep could be completely controlled—with restoration of perfect health to the animals—through top-dressing of the pastures with 2 lb/acre of cobalt chloride together with superphosphate, or, better still, with 200 lb/acre of cobaltized superphosphate (equivalent to 16 oz of cobaltous sulfate). The beneficial effect of such an application persisted for 3 to 6 years. Similar symptoms of cobalt deficiency of cattle have been observed in the New England States as well as in Canada.

Recent investigations suggest that cobalt is much more of an essential element than was formerly believed. It is now known to be required for the formation of vitamin B_{12}, which contains 1 atom of cobalt in each of its molecules and which has been termed "one of the most powerful factors in the health of all living things" (including plants). This vitamin appears to be intimately involved in the processes of sexual reproduction, and has come into medical prominence as being effective in the treatment of pernicious anemia of humans. (See also page 40.) In view of these facts, it can be expected that the cobalt nutrition of plants will receive increasing attention in the future.

Vanadium. Vanadium, though nearly always present in the soil as well as in the ashes of plants, has not as yet been connected with any specific function as far as the growth of plants is concerned. There are indications that this element plays a possibly important role in the life cycle of nitrogen-fixing bacteria, and it is very likely to be prominently involved in certain synthetic processes within the living plant. In spite of this uncertainty, vanadium has been included here because the chances are considerable that its influence is of significance equal to that of the other trace elements. The fact that this element appears to be present everywhere, and is always absorbed by plants only in minute traces, renders exact observation extremely difficult.

Uranium, Radium, Thorium, and Actinium. Uranium, radium, thorium, and actinium are likewise nearly always present in the soil and are absorbed by plants in very small amounts. Experiments carried out in Europe tend to indicate that radioactive elements are required by plants. (See page 44 for influence exerted.) It has been estimated that the radium content of the average topsoil—though it is so low that it is very difficult to measure—exceeds the needs of plants for optimal growth about 3,000 times.

Other Trace Elements. The actual importance, if any, of iodine, cesium, barium, strontium, lithium, titanium, nickel, and chromium is still rather uncertain. Iodine has been reported to stimulate growth in plants when applied as potassium iodide in a highly diluted overhead spray. Cesium, barium, strontium, lithium, and titanium may be active in certain physiological processes connected with the transport of other elements within the plant. Nickel is suspected of being involved in the synthesis of certain vitamins (vitamin P, for instance). Of chromium it has been reported that, in sand and water cultures, very small amounts of chromium salts produced a slight stimulation. Larger amounts of chromium proved to be toxic, and natural chromium toxicity has been observed, for instance, in certain soils of South Africa. Though most plants contain traces of these last-named eight elements in their tissues, the salts of most of them—even when applied in very small amounts—are quite toxic to plants.

Application of Trace Elements. Occasionally, the suggestion is made that the trace elements be added to the soil in the form of salts, and preparations of this type are sometimes offered under special trade names. Such a procedure is not advisable and actually is fraught with danger, since applications should be made only if one is sure that a deficiency exists, and amounts must then be very carefully controlled. That even a slight overdosage, or a local overconcentration, is likely to cause damage has been pointed out in the cases of boron, manganese, and zinc, as well as with several of the other trace elements. The best procedure to assure availability of trace elements will probably always be proper soil management, since in most instances the deficiency of trace elements is the result of wrong soil treatment. (See page 319 for fritted trace elements.)

FERTILIZERS. The fact that so little is known about the trace elements has caused them to be regarded by many in the light of a mystery, which has resulted in some rather strange notions. One of these is the frequently repeated claim that the use of "artificially" produced fertilizers, which are designated as consisting of "chemically pure" salts, would cause a deficiency of trace elements. This claim is easy to refute, since many of these maligned fertilizers, such as superphosphate, sodium nitrate, calcium nitrate, potassium nitrate, and others, have their origin in naturally formed mineral rock and, for this reason, do contain the trace elements. In other words, they simply are not chemically pure salts.

There are only comparatively few fertilizer salts—such, for instance, as the completely artificially produced ammonium sulfate or ammonium nitrate—which do not contain admixtures of trace elements, but these are rarely used persistently by themselves. Greater use of synthetic fertilizer salts, which will almost certainly become necessary in future, however, will increase the need of minor-element addition.

Manure or Compost. The advice to incorporate stable manure, compost, and other organic fertilizers in the soil, because these materials contain the trace elements, is perfectly sound. What should, however, be considered by those who advocate the exclusive use of organic fertilizers, and what usually is completely overlooked, is the fact that compost consisting of plant matter derived from a deficient soil is, by necessity, likewise deficient. So is the manure of animals fed on plants which were raised on deficient soil. In other words, locally produced compost or manure will serve to replace, at least in part, the elements which were taken out of the soil, but, except when feed for the animals is imported from elsewhere or when refuse from vegetables not raised locally is added to the compost pile, they cannot serve to add trace elements which were missing originally. The combined use of both organic and inorganic fertilizers will always remain the safest procedure.

POISONOUS ELEMENTS

Certain elements which are harmful to man, animals, or plants, such as arsenic, selenium, and fluorine, are also quite commonly present in the soil and are absorbed by most plants. The average amounts present or absorbed are so small that generally they can do no harm, but, in certain regions of the earth, one or another of these three poisonous elements is contained in the soil in amounts larger than can be considered safe.

Arsenic. Arsenic is contained in most soils but is generally absorbed by plants only in very small amounts, varying from 0.1 to 10 ppm, depending on plant variety and soil condition. No cases are known where plants have absorbed sufficient arsenic to be harmful to man or to animals, and this danger actually does not appear to exist. Injury, however, may be caused to the plants. Since plants absorb only limited amounts of arsenic even when plenty of it is present, it is evident that the injury must be indirect, and evidence is accumulating that large amounts of arsenic in the soil interfere in some manner or other with the availability of zinc. It has been observed that the annual spraying of orchards with arsenate of lead produced a rather considerable accumulation of arsenic in the soil, and that, when such an orchard was removed and the area was plowed for the culture of other crops, the soil proved unproductive (alfalfa especially, but also most cereals, showed retardation of growth or stunting) unless small amounts of zinc sulfate were applied.

On the other hand, it has been reported that certain crops, such as asparagus, potatoes, carrots, and tobacco, are tolerant of fairly high arsenic soil content, giving good results in spite of it. This would suggest that these plants are able to overcome the interference of arsenic with their zinc supply.

It appears, furthermore, that the composition and texture of the soil have a considerable influence on what concentration of arsenic may cause plant injury or may be tolerated. It was found that harmful effects from arsenic resulted much more readily in sandy soils than in clayey soils. The suggestion has been made to apply ferrous sulfate to alkaline soils or to lime acid soils in order to reduce the solubility of arsenates and therewith the injurious effects they are likely to produce. Such procedures cannot be generally recommended, however, since their effect depends upon a complexity of factors which are very difficult to assay.

Curiously enough, experiments have shown that low concentrations of arsenic (applied as calcium arsenate) are beneficial to plants, producing noticeable stimulation of growth which is believed to result from some sort of catalytic action.

In general, it appears that accumulation of arsenic in the soil is not as serious a danger as it is sometimes believed to be, though the availability of zinc will have to be watched.

Selenium

Considerable interest has been aroused by the fact that fairly large amounts of selenium are found in the soil in certain regions, and that the long-known alkali disease of horses and steers actually is a selenium poisoning. Fortunately, such soils are comparatively rare and occur only in regions with low annual rainfall, though selenium is present in small amounts in soils over very large areas. An interesting feature of this problem is that not all plants readily absorb selenium in toxic quantities. Those which absorb it in largest amounts require it for healthy development and grow only in regions where this element is present These latter plants—over 30 have been recognized—can therefore be used as indicator plants which reveal the presence of selenium. It has furthermore been found that these same plants serve as converters and play an important role in the production of toxic concentrations of selenium compounds in crop and forage plants.[6] The converter plant absorbs selenium compounds not available to other species and, in decaying into humus, leaves the selenium in a form which is readily taken up by other plants. Certain legumes, especially certain species of *Astragalus*, are most

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[6] Moxon, A. L., Olson, O. E., and Searight, W. V., *S. Dakota State Coll. Agr Expt. Sta. Tech. Bull. No. 2* (1939), and others.

notorious for acting in this manner and must, therefore, be considered as highly dangerous and undesirable weeds on seleniferous soils.

The danger of human poisoning through the consumption of flour from grain grown on seleniferous soil is quite negligible, since selenium soils are always local, and flour mills usually process vast amounts of grain originating from various regions, thereby producing a thorough and safe mixture. Cases of human selenium poisoning have been reported from Mexico where vegetables were consumed which had been raised on highly seleniferous soil, while the local water supply, at the same time, had an unusually high selenium content.

Fluorine

The fluorine content of soils varies widely, from traces to as much as 7,000 ppm. A soil content from 100 to 200 ppm of fluorine is quite common. Although this may seem rather alarming, since fluorine in itself is poisonous, no actual danger appears to exist. This is because land plants always contain only very minute amounts of fluorine, and these amounts remain quite constant regardless of the fluorine content of the soil. No harmful effects on man or animals have so far been reported, even when plants which had been raised on soils with known high fluorine content were used for food.[7]

The fluorine content of phosphates appears to be without significance, except that phosphorus availability decreases in proportion to increasing fluorine content. (See page 206.)

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[7] W. O. Robinson and Glen Edgington report [*Soil Sci.*, **61**, 341 (1946)] the fluorine content of plants raised on soil containing 137 ppm near the surface and 172 ppm in the subsurface as follows: alfalfa, 2.1 ppm; cabbage, 3.4 ppm; lettuce, 11.3 ppm; and spinach, 28.3 ppm.

3. THE ORGANIC CONTENTS OF THE SOIL

MAIN GROUPS OF ORGANIC SUBSTANCES

Organic matter, often called *humus,* is one of the most important constituents of living soil, as far as plant growth is concerned. For practical purposes as well as for a clear evaluation of the relative availability of humus, it is necessary and important to distinguish between two main groups of soil organic substances which differ vitally from each other in biological and physiological properties.

The total amount of organic matter contained in a given soil consists of: (1) reserve organic matter, viz., that part which is still undecomposed or is in process of decomposition and which, through continued chemical and biological influences, gradually changes into humus; and (2) humus, viz., that part which is fully decomposed to the colloidal state and which therefore is able to fulfill the important functions outlined on pages 27 and 178.

To know at all times in what proportion reserve organic matter and humus are contained in his soil is of vital importance for the practical farmer and gardener, since, without this knowledge, he cannot properly gauge the condition of his soil, on which present and future productiveness depend. The reserve organic matter is determined by establishing the amounts of total organic matter as well as of humus and by subtracting the latter from the former.

GENERAL PROPERTIES OF HUMUS

The many excellent qualities of humus materials are described below; it is well to remember that in open field culture—the only type of plant culture which really matters in the world's food production—humus is well nigh indispensable.

Significant, however, is the fact that the level to which the organic content of soil can be raised by adding compost or manure, or both, does not depend upon the amount added but is governed by climatic conditions. The mean temperature is the main deciding factor in establishing a humus-content level through its influence on the speed of the breakdown of organic matter. Soil nitrogen level also has an important influence.

Use of Inorganic Fertilizers to Increase Humus Content

It is frequently stated that inorganic fertilizer alone cannot maintain the soil in permanently healthy condition and may, in fact, ruin it if the humus content of the soil is not maintained at a reasonably high level. This statement is quite true in itself but contains the danger of possible misinterpretation. The unintelligent use of artificial fertilizers, without previous soil testing, can indeed reduce the productivity of a soil, especially if only one type of fertilizer is chosen and is used too freely or repeatedly. On the other hand, it has been proved that artificial fertilizer alone, if used correctly—which means based on soil tests and in such a manner as to establish a proper nutrient balance—actually *raises the humus content of the soil.* The more vigorous development of the plants and the farther spread of their roots result in larger amounts of plant residues—dead organic matter which turns into humus—being left in the soil after the crop is removed. Over a 15-year test period, during which a number of different types of crops received only mineral fertilizer every year and no organic fertilizer, the humus content of the soil increased by over 40 per cent (West Virginia Agricultural Experiment Station).

This example shows that so-called artificial fertilizers need not ruin a soil. If used intelligently, they can even bring about a steady improvement. The emphasis placed on the increase in humus content of the soil shows, however, that much more is at stake than merely the supplying of freely available nutrients.

Living soil is an immensely complex matter which, for proper treatment, must be understood in all its aspects. To focus attention on one point only and to argue for or against mineral fertilizers or organic fertilizers is futile. Both are of indisputable value and importance, and, for soil improvement and the maintenance of soil fertility, the two must be brought into proper relation with each other.

Values of Humus

The qualities of humus which are of greatest interest and value for the practical farmer and gardener must be considered first. The subsequent discussion of the chemical constituents of organic matter will then be much easier to follow.

One of the most valuable qualities of humus is its ability to absorb and retain water, thus holding it in reserve and preventing it from being lost in percolation or through surface runoff. At the same time, humus acts as a sort of filter, retaining a large part of the nutrient salts dissolved in the soil solution, even after the water has disappeared, and releasing the nutrients again slowly when water is added. Its colloidal character (page 29) gives it cohesive power, which means that it is able to hold soil particles together. In this manner it serves to render light sandy soils more retentive of water and nutrients, whereas in heavy clay soils it increases the pore spaces by tying the very small soil particles together into groups. (See Chapter 11.) Increased pore space means better aeration and improved drainage. This two-way action in different soil types is as curious as it is important, though it is readily understandable that the incorporation of raw fibrous organic matter will result in the loosening up of heavy soils.

The dark color of humus also is of value to plant growth. Black absorbs and retains heat, whereas white reflects it and remains cool. The dark humus, therefore, serves to render heavy, cold soils warmer, and tends to equalize the often sudden and very undesirable fluctuations of temperature in light soils.

CHEMICAL CONSTITUTION OF SOIL ORGANIC MATTER AND HUMUS

From the chemical viewpoint, soil organic matter consists of undecomposed, decomposing, and decomposed organic matter, though newly formed organic compounds are included in the end product.

As is apparent from the above very elastic definition, soil organic matter is extremely diverse in composition. That this must be so, that organic matter cannot be uniform in composition, is indicated by the wide variety of organic materials from which it may originate. In nature, humus may be formed from plants and plant parts, such as leaves, needles, fruits, roots, and wood, as well as from the bodies of all kinds of dead animals—from large mammals to insects, worms, and the millions of microorganisms. This dead organic matter is subjected to a continuous chemical and, especially, biological decomposition by processes which are further elucidated in Parts II and III.

Humus, the end product, unavoidably contains many of the same elements and compounds which formed the ingredients of the organic matter from which it originated. In addition, many new organic compounds which were formed during decomposition, and which were not contained in the original organic matter, are present also.

Important Substances in Humus

The chemist has at his disposal a wide variety of methods which enable him to extract the various substances contained in humus. Many of these substances have been identified, but quite a few others still evade present analytical methods, though their presence can be proved. To give an idea of the enormous variety of organic substances present in soils, some of those which have been identified are enumerated:

(1) Carbohydrates (compounds containing the elements carbon, hydrogen, and oxygen), including cellulose, hemicellulose, starch, various types of sugars, pentosans (compounds somewhat intermediate between starch and sugar), pectin (found in ripening fruits), and glycogens (which must be traced to animal organisms).

(2) Lignin substances, which come from the woody skeleton of plant bodies and plant cells.

(3) Proteins, rather complex compounds, consisting of carbon, hydrogen, oxygen, nitrogen, sulfur, and sometimes phosphorus and iron. Various types of proteins are commonly present in animal as well as in plant organisms. Their decay results in the formation of amino acids which can be readily identified in the soil and which, in further decomposition, have for their end product ammonia or ammonium salts. (See Part II.)

(4) Fats, and various types of waxes, oils, and resins.

Lignin as a Source of Humic Acid. Most of the above-mentioned substances are rather rapidly decomposed by microorganisms into simpler compounds (see Chapter 4) and eventually dissolve largely into the elements of which they consisted originally. The lignin substances, however, show considerable resistance to biological decomposition, and, decomposing very slowly, they represent a rather stable component of soil organic matter. The most essential ingredient of all lignin substances is humic acid which, at the same time, represents the most vitally important component of humus. (See page 178.) The chemical constitution of lignin, though not completely understood as yet, has been proved to differ in different types of plants. Because of the vital influence exerted by humic acid on the dynamic processes continuously occurring in a living soil, the details supplied in the following paragraphs deserve careful consideration.

Humic Acid. Humic acid is present in nearly all soils in varying amounts. In chemically pure form it represents a dark reddish-brown powder which is practically insoluble in water.

SOLUBILITY. An important property of humic acid is that, if brought into contact with certain bases, it forms salts. (See page 120.) Though most of these salts (such as those formed with calcium, magnesium, iron, aluminum, and manganese) are likewise nearly water insoluble, some of them (such as the humic acid salts formed with potassium, ammonia, and sodium) are readily soluble in water. This solubility in certain alkaline solutions, produced in the soil under certain conditions, is highly significant.

In addition, free humic acid and quite a few of its water-insoluble salts are soluble in certain neutral solutions. These are solutions of the salts which potassium, ammonium, and sodium form with certain organic acids, such as acetic, citric, tartaric, and oxalic acids. Such humic acid solutions in salts of the above-mentioned acids remain stable even at a slightly acid reaction of the liquid (in the range of pH 5 to 7). (See page 89 for explanation of pH.) Since such organic acids are commonly found in nature, their salts with potassium, ammonium, and sodium also are frequently present in the soil. No doubt remains, therefore, that humic acid and many of its salts are soluble under a fairly wide range of circumstances. Solubility, however, is a step in further decomposition, and this involves indirectly the nutrient availability for plants. The latter is impaired when humus is lost. (See page 244.)

COLLOIDAL CHARACTER OF HUMIC ACID AND ITS SALTS. Of equal importance is the colloidal character of humic acid and its salts. The special properties of colloids in general will be explained later when mineral colloids are discussed (page 70), but it may be pointed out here that organic colloids, though similar in function, differ from mineral colloids by being amorphous. Like other amorphous substances, such as glue and gelatin, humic acid and its salts are able to absorb and to hold considerable amounts of water. This process is accompanied by swelling to several times the original size and by the formation of a jellylike matter. In the soil, such action results in the preservation of moisture and, at the same time, becomes of considerable value in making more permanent the soil crumbs, formed through cohesion of the soil particles.

BASE EXCHANGE OF COLLOID HUMUS. One more of the many valuable properties of humic acid is its ability to function in what is called base exchange (or cation exchange). This rather complex process is explained later in detail (page 73), and only an introduction to the subject will be given here.

To understand this process, it must be understood first of all that the various mineral elements which are to be considered as potential plant nutrients, such as potassium, phosphorus, calcium, magnesium, iron, aluminum, and manganese, are, in their elemental state, of no interest at all as far as plants are concerned. The only element which can be used directly by higher plants is oxygen, though elemental nitrogen and sulfur are assimilated by certain microorganisms and, in this manner, are made available to higher plants.

Preliminary Explanation of Ions. Plant nutrition deals with a distinct phase or state of the various elements or their compounds. In this state minute particles of substances are electrically charged (positive or negative, as the case may be) and are extremely active. Because of their electrical charge, these particles are inclined to move about, following the attraction of the opposite pole, represented by the various soil colloids. Their movements are governed by the compulsion to establish electrical equilibrium. These traveling, electrically charged particles of substances are called ions and must not be confused with the electrically inactive molecules of the elements or compounds themselves. The various chemical reactions which result from the fact that these minute particles are always ready to change places (are exchangeable), from colloids to soil solution and vice versa, under the influence of their electrical charge, have far-reaching consequences in the soil. In fact, it has been stated (Marshall, 1935) that, next to photosynthesis (see page 100), ion exchange is the most important chemical reaction in the whole domain of agriculture.

Effect of Base Exchange. A few samples of this exchange process may be given. Calcium ions appear to be particularly easy to detach from the soil colloids and are readily replaced by others. If calcium is replaced by hydrogen, increased soil acidity is the result, because the calcium then usually is lost in drainage. Since this is a very common occurrence in nature, most natural soils tend gradually to become more acid. If lime is added to acid soil, the opposite happens, and the calcium ions, through mass action, push the hydrogen ions off the colloids, with the result that soil acidity is lessened. If one of the readily water-soluble salts of potassium, ammonium, or sodium is added to soil and comes into contact with the water-insoluble calcium salt of humic acid, some of the calcium ions will change places in ion exchange and the humic acid will form new soluble combinations with the potassium, ammonium, or sodium salt ions, as the case may be.

Important Function of Base Exchange. Ion exchange fulfills a very important function, whenever fertilizers are added to the soil, though its action is equally significant as far as the naturally present plant nutrients are concerned. The important point to be understood is that the various elements and compounds which, in their ionic state, are thus loosely held (adsorbed, not absorbed) by the soil colloids represent the nutrient reserve. Since they are exchangeable in ion exchange, they are only temporarily out of circulation and become available to plants and microorganisms as soon as they are detached in one way or another, as is explained later (page 76).

The humic acid content of a natural soil or correctly treated cultivated soil—meaning soil to which humus in one form or another is added regularly—does not increase beyond a certain level, remaining fairly constant once this level is reached. This suggests that though this substance is exceptionally resistant to decomposition it nevertheless is used up slowly.

Other Substances in the Soil

The presence of all the constituents of soil organic matter which have been mentioned thus far can readily be proved, and many of these substances have actually been extracted from soils. Others, however, are present in such minute amounts that extraction is extremely difficult, so that, in some instances at least, their presence can only be deduced from their apparent influence on plant development. A number of such substances, which are deserving of attention for a true evaluation of the importance of soil organic matter, are discussed in the following paragraphs.

Growth Substances. As previously stated, soil organic matter also contains, besides undecomposed and decomposing organic matter, the products of their decomposition as well as certain newly formed organic compounds or substances. The latter are of considerable interest, especially those which are known to be derived from the decomposition of proteins and carbohydrates. (See page 28.) The biological processes which are involved in the breakdown of the rather complex proteins and carbohydrates into simpler substances are further explained on page 165. In this splitting-up process the proteins are gradually reduced to albuminoses, peptones, amino acids, and, finally, to carbonic acid and ammonia. The carbohydrates, in particular cellulose, are responsible for the formation of various fatty acids, such as acetic acid, propionic acid, and butyric acid, as well as of various other substances.

DERIVATIVES OF INDOL AND SKATOL. These products of biological decomposition are involved in the formation of new substances which are rather complex in composition but which have valuable properties as far as plant life is concerned. It is known that during putrefaction (rotting or decay), which means whenever proteins are decomposed, certain compounds deriving from indol and skatol are always formed. In the presence of fatty acids, such as those mentioned above as resulting from the decomposition of carbohydrates, the indol derivates enter into still more complex compounds, of which indol acetic acid is one of the simpler ones. Since dead bodies of animals, as well as decaying plants, with their decomposing carbohydrates, constitute the source of all soil organic matter and are, therefore, present in all fertile soils, it must be expected that indol acetic acid likewise is not only present but is being formed continuously.

Indol Acetic Acid. Attempts to extract indol acetic acid from soil have succeeded, as is explained later, and the fact has been established that in fertile topsoil it is present in larger amounts than in soils lacking in humus or in subsoil. Though the relative amounts are never large, they fluctuate between 1 and 50 micrograms (mcg) in 1 kg of soil; this is significant. In addition, indol acetic acid is always present in animal excrements and has been found in relatively large amounts particularly in the urine of pregnant cows. In consequence, stable manure must be considered as a fairly reliable source of indol acetic acid, though this acid also occurs naturally in living plants, not only in fungi but also in higher plants.[1]

Why should anyone be concerned with the indol acetic content of the soil or be interested in adding it?

Plant Hormones. The words "plant hormones," "phytohormones," "auxins," and "growth regulators" are mentioned so frequently even in gardening magazines that most people who are interested in plants have become familiar with them. Some of the substances to which these designations are applied are offered for sale by seedsmen. One of the first such substances with which experiments were carried out was indol acetic acid, which proved useful in stimulating root development on cuttings. Other similar compounds are now used to prevent premature fruit drop on fruit trees, to assist plants in getting over the shock of transplanting, to produce seedless fruits, or to eradicate weeds. The application of certain "growth hormones" directly to the soil resulted in the production of more and larger fruits on tomato plants.

In view of the rather sensational developments of late years, it is pertinent to recount that 80 years ago (in 1880) the famous naturalist Charles Darwin reported in his work "the power of movement in plants," an observation which he considered as suggesting the presence of some such special agent, though he did not attempt to give it a name. This observation concerned young grass seedlings which were exposed to light

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[1] Van Overbeck, J., "Agricultural Chemistry," p. 427, D. Van Nostrand Co., Inc., New York, 1950.

coming from one side only and which did not bend over toward the light when their growing points were covered with dark caps or were cut off.

The Avena Test. Thirty years later Boyesen Jensen [*Ber. deut. botan. Ges.*, 20, 118 (1910)] described similar experiments with oat seedlings and made the definite statement that the bending of plants toward the light is governed by chemical substances contained in the plants. This was confirmed through further experiments carried out in Holland, where, in 1928, Went published his now classical paper describing the Avena test. (*Avena* is the botanical name for oat.) This test serves to estimate the amount of auxins (growth-promoting or influencing substances) contained in a plant nutritive solution.

The procedure employs oat seedlings with their growing points removed, so that the growth substance normally contained in the growing points cannot influence the behavior of the seedlings. The decapitated oat seedlings are placed in the solution which is to be tested and which has been jellified through the addition of agar-agar. When exposed to controlled light under controlled laboratory conditions, the degree of bending of the oat seedlings toward the light permits a fairly accurate estimate of the amount of "plant-growth substance" contained in the solution.

By means of this test as well as through other methods, the presence of indol acetic acid and similar substances in soil extracts has been definitely proved, and it must be assumed that they get into the soil as components of decomposing organic matter. Since the favorable influence of the various auxins on root development and plant growth has been ascertained beyond doubt through numerous investigations, their presence in the soil assumes considerable importance. Their actual effect on soil fertility and crop yields cannot be estimated at present, because the various auxins appear to be rather specific in their action, and the same auxin does not have the same effect on different kinds of plants.

Indol derivates, such as indol acetic acid, indol butyric acid, and indol propionic acid, appear to be most commonly present in plants as well as in the soil, though other auxins, some of still unknown or incompletely known composition, have recently been isolated from various types of organic matter. Over 50 similar but synthetically produced substances are known to influence plant growth in one way or another. These latter will not be enumerated here, since there is very little chance of their being present in soil.

Antibiotics. Seemingly in opposition to the group of growth-promoting substances is another group, the antibiotics. Their name describes their action, which consists in the suppression of life. Fortunately, this action is not general but apparently extends only to the suppression, or hindering of the development, of certain microorganisms. How occasionally, through interference with a beneficial microorganism, it may indirectly affect the development of higher plants will be shown later. Significant is the fact that antibiotics appear to be strictly selective, which means that a specific antibiotic will affect only a certain definite group of bacteria or other microorganisms. Besides, the production of antibiotics is a defensive measure directed mainly against certain bacteria which are likely to interfere or to compete with the respective fungi. That these suppressed groups happen to include many generally harmful bacteria, those which cause diseases in plants and man, may be no more than a happy coincidence, but it undoubtedly contributes to maintaining the balance of nature.

SAPROPHYTIC FUNGI PRODUCERS OF ANTIBIOTICS. Most of the antibiotics which are of interest in relation to soil are by-products of the life cycle of certain fungi, and, of particular significance, these fungi are known to be saprophytes, which means that they live on decaying organic matter. The latter fact suggests that these antibiotic-producing fungi are the probable occupants of the organic matter which is incorporated in the soil by the farmer or gardener. Actually, there is a certain amount of evidence. It has been observed (as reported by Groosbard) that the incorporation into the soil of partly decayed straw or lawn clippings results in a considerable increase of saprophytic, antibiotic-producing fungi. Though results are still inconclusive, it is possible that the superior results frequently obtained with a mulch (a surface covering) of chopped straw on ornamental perennials and other plants may, at least in part, be due to the suppression of harmful bacteria through antibiotics produced by the fungi living on the straw. It must be assumed, furthermore, that so-called green manuring, the shallow plowing under of green plants for the purpose of increasing soil fertility, likewise results in the production of soil antibiotics, which may have a share in the beneficial effects obtained. In order to avoid misunderstanding, it must be emphasized, however, that many bacteria and actinomycetes likewise are able to produce antibiotics.

INDIRECT INJURY TO A HIGHER PLANT CAUSED BY AN ANTIBIOTIC. A rather interesting proof of the presence of antibiotics in the soil, which incidentally shows that these substances can occasionally be harmful to higher plants, is furnished by a report of the Forestry Commission of Great Britain. This report concerns the Wareham heaths in England, where pines, planted in an effort at reforestation, did not thrive, in spite of the fact that climatic conditions appeared to be favorable. Examination of the soil revealed the presence of a blue mold fungus which, in laboratory cultures, produced an antibiotic, gliotoxin. This substance hinders the growth of a number of microorganisms and, unfortunately, also suppresses a mycorhizal fungus which is necessary for the healthy development of pine trees. (See also page 50.)

EFFECT OF ANTIBIOTICS ON ANAEROBIC BACTERIA. As an indication of how far reaching the influence of antibiotics in the soil may be, a further example is given: It has been known for some time that certain low fungi as well as bacteria are able to live without direct access to air (see page 52), and, therefore, both *can* exist in the soil at considerable depth. Experience has shown, however, that bacterial life becomes more scarce the farther down one descends in the soil, until one reaches a depth at which fungi predominate completely and bacteria are absent.

This fact is of practical importance in the digging of wells for drinking water where, for sanitary reasons, all bacterial contamination must be absolutely prevented. The well digger knows that to reach the subsurface water table, where an ample supply of water is assured, is only one of his problems. He realizes that he must also dig down below the range of bacteria, and he knows that as soon as he reaches a level where only fungi are present in the soil, his water supply is safe. All he has to worry about from then on is to prevent contamination of the water from above by lining the inside of the well with cement or mortar.

The actual reasons for this proved absence of anaerobic bacteria (bacteria which can live without access to air) and the predominance of fungi in the lower soil levels—often to a depth of many yards—are debatable. The theory has been advanced, however, that the ability of the fungi to produce antibiotic substances gives them an advantage over the bacteria. Under conditions such as prevail so far below the soil surface where competition for the much scarcer organic nutrients must be very keen, the fungi may thus be enabled to gain the upper hand.

ANTIBIOTICS EMPLOYED MEDICINALLY. The previously discussed plant hormones, or growth-promoting substances, and the antibiotics have come to public notice only in comparatively recent years. Everybody has heard, for instance, of penicillin, frequently termed in popular writings a miracle drug. It is used in medicine to stop various types of bacterial infection such as pneumonia, certain types of chest colds, or wound infections, and is an antibiotic produced by the mold fungus *Penicillium notatum.*

Streptomycin, product of another mold, has been found effective in the fight against a different group of disease-causing organisms, such as those which cause certain types of tuberculosis. "Actidione," an antibiotic by-product in the manufacture of streptomycin, has shown great promise in the control of mildew on many types of plants.

"Chloromycetin," effective against typhus and typhoid; "Aureomycin," which has come into prominence as being effective against virus-induced types of pneumonia; and "Terramycin,"[2] effective against Rocky Mountain spotted fever, are other well-known antibiotics. Others are being added continuously to the list of known substances of this type. Considerable advancement in this science can be expected in the near future, and investigations will undoubtedly disclose also much-needed additional information on soil antibiotics. As far as the latter are concerned, investigators are greatly handicapped by the complex nature and wide variety of the composition of soils, as well as by the fact that fertile soil, which is of greatest interest to the plant grower, teams with a multitude of forms of microorganisms. Even under laboratory conditions, where the nutrient solutions employed are sterile, it is by no means easy to succeed with the culture of fungi and to cause them to produce antibiotics freely. It required many years of study to work out satisfactory methods for the cultivation of the mold *Penicillium notatum* in efforts to produce penicillin in sufficient quantity.

ANTIBIOTICS IN HORTICULTURE. As far as soil treatment is concerned, it appears worth while to keep in mind the suggestion made on page 34, viz., that the incorporation of organic matter, which is rich in carbon—such as straw or sawdust—provides favorable conditions for the growth of antibiotic-producing fungi. (See page 168 for precautions which must be observed to prevent soil impoverishment.) Such soil antibiotics serve mainly in the control or partial control of soil-inhabiting pathogenic organisms affecting the roots. Recent experiments[3] have shown, however, that dusting of seeds with small amounts of the antibiotic "Actidione" could completely control covered smut of wheat. This suggests that the presence of certain antibiotics in the soil might serve in a similar manner, though concentrations in the field can probably never be high enough to produce more than very partial suppression. Greenhouse experiments[4] have produced evidence that such antibiotics as aureomycin, streptomycin, and griseofulvin are absorbed by the roots of plants (oats, lettuce, soybean, and lima bean) and are transported to the leaves and stems. At first glance this seems to support the claim, made by certain "organicultists," that the incorporation of organic matter in the soil will render plants immune to diseases through the absorption of antibiotics. Unfor-

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[2] "Terramycin" applied to the soil—at the rate of 5 ppm of water—produces a considerable speed-up in the growth of seedling plants, approximately doubling it. It is believed that this effect results from the suppression of certain undesirable microorganisms. Penicillin appears to have a similar effect when applied at the rate of 10 units/g of soil. (Chas. Pfizer & Co. Laboratories, Brooklyn, N.Y.)

[3] Henry, A. W., Millar, R. L., and Peterson, E. A., *Science*, p. 90 (Jan. 25, 1952).

[4] Anderson, H. W., and Nienow, J., *Phytopathology*, **37**, 1 (1947); Blanchard, F. A., and Diller, V. M., *Am. J. Botany*, **38**, 3 (1951).

tunately, this does not appear to be the case, because the amounts which are likely to be absorbed by plants in the field are so minute that they can hardly be effective at all, and, when artificially supplied in amounts which are large enough to produce immunity, the plants are likely to be injured. The injection of antibiotics into the stems of plants, for instance into the trunks of trees, however, appears to be promising, and this procedure is likely to find more frequent application in the future.

Vitamins. In somewhat the same class of uncertainty but possible promise for soil management belong the vitamins. These substances also have received much publicity, and it is commonly known that deficiency of certain vitamins in the human diet causes certain diseases, such as rickets, beriberi, scurvy, and pellagra. Until vitamins were discovered and their significance was understood, these diseases remained rather mysterious and hard to cure, though the American Indians did know how to cure scurvy.

Old records have revealed that a French exploring party, headed by the famous Jacques Cartier, being near death from scurvy, was found by Indians and cured by them with a tealike infusion from the leaves and bark of some not clearly identified conifer which they called *annedda.* (Spruce needles are known to have a comparatively high content of vitamin C, which is the antiscorbutic vitamin.) Thus the Indians employed vitamins very intelligently, without knowing anything about them. Their remedy was based simply on experience. Most of the important vitamins required for human health enter man's diet through the plants which he uses for food. The French exploring party of more than 400 years ago had lived exclusively on meat. Nowadays, most of the vitamins used medicinally are produced synthetically, but man still does, and undoubtedly always will, depend on proper food habits for the prevention of vitamin deficiency with its usually very unpleasant and often serious consequences.

FUNCTION OF VITAMINS IN LIVING PLANTS. The fact that in nature so many of these all-important vitamins are found in plants made it logical to suppose that they are required also for the health of the plants themselves. This has actually been proved through careful experiments carried out by a large number of investigators. The conclusion reached is that vitamins are just as important and indispensable for the plants which synthesize them as for the animals and humans which consume the plants. The accumulated proof shows that vitamins function in the plant as coenzymes or fragments of coenzymes. They are intimately connected with the processes of metabolism going on within the plant cells and play an important role in photosynthesis and respiration. (See page 100.)

Hormones, or auxins, discussed previously, are distinguished by their specific action on the morphology of the organism. They are connected directly with the formation of organs through their influence on root development, growth of shoots, flowering, etc. The fact that vitamins and auxins have frequently been found to be interdependent in their action is particularly noteworthy.

VITAMINS SYNTHESIZED BY PLANTS. The following vitamins are known to be synthesized by plants and, therefore, are contained in plant tissues:

Carotinoids (provitamin A). Plants do not seem to be able to synthesize vitamin A itself.
Thiamin (vitamin B_1) antineuritic (beriberi) vitamin.
Riboflavin (vitamin B_2) growth vitamin.
Pyridoxine (vitamin B_6).
Ascorbic acid (vitamin C) antiscorbutic vitamin.
Ergosterol (provitamin D_2) (occurs in yeast); (provitamin D_5) (occurs in soybean). Plants apparently do not synthesize any of the D vitamins.
Alpha-tocopherol (vitamin E) antisterility vitamin.
Biotin (vitamin H).
Phylloquinone (vitamin K) antihemorrhagic vitamin, serving as catalyst in photosynthesis and involved in the process of nitrogen reduction within the plant.
Inositol (bios I).
Nicotinic acid (vitamin B_2 complex) antipellagra vitamin.
Pantothenic acid (of uncertain position, apparently a growth factor).
Various others still only incompletely identified.

This is an impressive list and shows the importance of plants as sources of vitamins for human and animal consumption.

As far as investigation of soils is concerned, the answers to the following questions are vital.

(1) Are vitamins present in the soil?
(2) Can any advantage be gained by adding vitamins to the soil?
(3) Can the vitamin content of plants be increased through the type of fertilizer used?

PRESENCE OF VITAMINS IN THE SOIL. Investigations carried out in particular at the University of Switzerland have proved that certain vitamins, such as thiamin, biotin, pyridoxine, and inositol, are regularly present in fertile soils. Some of these vitamins, in particular biotin, were found down to the astonishing depth of 8 m (24 ft), though it must be assumed that they reached the lower soil levels only through leaching from above. These vitamins get into the soil partly through the decomposition of plants which contain them. A regular and steep rise in the biotin content of the soil was observed every autumn immediately after the trees had shed their leaves.

Vitamins are produced also by certain microorganisms which live on decaying organic matter and which are able to synthesize these vitamins in very much the same manner as do the higher plants. These microorganisms live in the uppermost few inches of soil, called the topsoil.

The main significance of the vitamin content of the soil lies in the fact that numerous microorganisms which make valuable, and even indispensable, contributions to the fertility of the soil cannot synthesize these vitamins, yet cannot live without them.

ADDITION OF VITAMINS TO SOIL. Evidence is accumulating that, under certain conditions and with certain plants, application of vitamin B_1 to the soil can definitely be helpful. It has been established that the B vitamins, more than 10 of which have so far been identified, are so-called metabolites, serving as coenzymes in a variety of metabolic processes within the plant. Most plants, though, appear to be able to synthesize these vitamins readily. Besides, vitamin B_1—and undoubtedly others also—is freely available in any normally fertile soil which contains a reasonable amount of organic matter.

With certain plants, such as cosmos, however, the ability to produce these required vitamins is strictly controlled by the temperature. At a temperature below 65°F, cosmos shows distinct retardation of growth resulting from lack of B vitamin, and application of vitamin B_1 restores it quickly to full vigor even at temperatures below its optimum.

The same appears to apply to the genera kalanchoe, camellia, bougainvillaea, arbutus, eucalyptus, and *Ceratonia,* though their optimum temperatures are probably lower than for cosmos. North of their zones of hardiness, these plants are generally treated as cool greenhouse plants, and it is under these conditions in particular that they have been found to respond most favorably to vitamin B_1 applications, either in the cutting or seedling stage or in transplanting.

What other plants react in the same manner still requires further study, but it is quite sure that not all plants do. Apparently, not all plants employ B vitamins for these same functions, and some probably do not use it at all. Those which do are unlikely to respond in the same manner to the same type of B vitamin. For these reasons, a general and indiscriminate application of vitamin B_1 to plants cannot be recommended.

EFFECT OF FERTILIZER ON VITAMIN PRODUCTION. The question whether it is possible to influence the vitamin content of food plants indirectly through the use of a particular type of fertilizer is singularly intriguing and is frequently under dispute. It can be answered with a straight "no." The only thing that counts is that the various raw materials (elements and compounds) which the plants need to synthesize vitamins are present and available, but it makes no difference whatsoever whether the required nutrients are offered in organic or in inorganic form. Numerous experiments, carried out by a great many investigators and extending to such important food plants as wheat, rye, Brussels sprouts, cabbage, spinach, lettuce, carrots, onions, potatoes, and others, have produced no significant difference in vitamin content, whether the plants were raised with artificial fertilizer or natural fertilizer or with both of them together.[5] The capacity of plants for vitamin synthesis and accumulation is controlled by hereditary factors, and the maximum content depends on the race or variety, not on the nature of the fertilizer supplied. The maximum can be increased only by crossbreeding high-capacity strains. It must be understood, however, that a favorable fertility level of the soil as well as a proper nutritional balance are definitely required for a high vitamin content.

VITAMIN B_{12}. Somewhat in a category by itself is vitamin B_{12}. As far as is known at present, only lower plants, such as certain bacteria, fungi, and algae, are able to synthesize this important vitamin. Herbivorous animals, such as cows, sheep, and horses, apparently obtain their supply through the intermediary action of the bacteria which inhabit their intestinal tracts and which synthesize vitamin B_{12} from the plants these animals eat—provided that these plants contain sufficient amounts of cobalt. It seems that higher plants cannot synthesize vitamin B_{12}, and they probably have to obtain their supply directly from the soil. Hogs also seem to obtain vitamin B_{12} from the soil, which these animals are in the habit of eating, whereas chickens get it from their own old droppings or from horse manure, when they have a chance to pick in it. Fish meal, usually included in chicken feed, also contains vitamin B_{12}. Man has to obtain vitamin B_{12} from various proteinic foods, in particular, liver, which has long been prescribed as essential in the diet of anemic people. (See also page 20.)

There still is a good deal remaining to be learned about the role played by the various vitamins in the life of plants as well as about the manner in which they are synthesized in nature. The above brief description attempts merely to summarize what is known at present.

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[5] Schopfer, W. H., "Plants and Vitamins," pp. 228-331, Chronica Botanica, Waltham, Mass., 1943.

SUBSTANCES CAUSING HEREDITARY CHANGES IN CELLS OF PLANTS

To give as complete as possible a description of soil, it is necessary o digress somewhat from the subject under immediate discussion in order o explain still another group of substances and processes. Though still ncompletely understood in their relation to soil, they are of far-reaching ignificance. To be considered now is the possibility of the presence in oil of substances which cause hereditary changes in the cells of plants, esulting in *mutants.* Mutants, in nature, are spontaneously appearing ew varieties which did not result from crossbreeding and which, in ucceeding generations, breed true from seed. (The geneticist avoids the xpression "new variety" and, instead, speaks of new "inborn traits.")

hromosomes and Genes

To bring these strange and fascinating phenomena into clear focus, t is necessary to recount a few facts concerning the principles of heredity. t does not belong within the framework of this book to explain the rocesses of plant cell division or the means by which the normal ferilized cell, during division, distributes equally to both sections the ll-important hereditary matter, decisive for the ultimate development f the plant. These details must be looked up elsewhere. All that is ecessary for an understanding of what follows is to bear in mind that, luring cell division, the hereditary matter separates into distinct stringike pieces called *chromosomes,* which can be seen and even counted nder a strong microscope. Because of the complexity of the hereditary haracteristics which are being passed on in this manner, it has been leduced that the chromosomes cannot be the bearers of individual traits; ather, they must transmit groups of related and interdependent characeristics. This means that, by necessity, the chromosomes themselves nust consist of still smaller particles. These latter are termed *genes* and re comparable to the molecules (smallest of atom complexes of the hysicist). Ultra- and electron microscopes actually have permitted the listinguishing of these minute bodies within the chromosomes.

Production of New Species by Hybridization

The science of heredity, like most of the sciences, is in continuous flux, and the vast amount of research of recent years has produced a large number of theories. Any attempt to describe in simple terms what happens when two different varieties of the same plant species are crossfertilized is, at present, almost sure to be challenged by one scientific faction or another. A book on soils, however, cannot possibly include details of this intricate matter. It may only be stated here that, under controlled conditions, it is possible to create through cross-fertilization and subsequent selection new types of plants which will come true from seeds. The many new and improved varieties of annual summer flowers and vegetables which are offered every year by seedsmen are proof of this fact.

It is known now that, in nature, new types of plants can be expected to originate in this manner only in very rare instances. That this must be so becomes readily evident when one considers that isolation of the hybrid and prevention of back cross-fertilization with the parents or with other unstable hybrids is the main requirement for success. To be sure, hybrids do occur in nature, but in most cases they are found only as isolated individuals and, when their seeds are sown, one usually discovers that they are unstable.

Mutation as Main Cause of Species Origin

All this has nothing to do with soil, but it is indispensable for an understanding of the speculations which follow and which concern the eternal question: How do new types of plants originate in nature, and what role, if any, does soil play in the process? It is now generally believed that the main cause of the origin of new species is mutation. Mutants appear here and there, not very frequently but fairly regularly, without apparent rhyme or reason, in otherwise normal colonies of plants. In nature, such mutants usually crossbreed with normal plants, but, because they contain new and stable combinations of characteristics, which are handed down to succeeding hybrid generations, they may, and occasionally do, result in the fixing of superior qualities if the latter constitute an advantage in the fight for survival. A plant with superior equipment for survival will gain the upper hand and, in this manner, new species may indeed originate in nature.

Internal and External Causes of Mutation. Investigation under powerful microscopes has revealed that the internal cause of the sudden change which results in mutation centers in the chromosomes (page 41). It has been found—and these findings are attested by microphotographs—that occasionally something happens to interfere with normal cell division, which may even be temporarily arrested in such a manner that the chromosomes are prevented from separating into equal halves when division is resumed. The chromosomes, which in each type of plant are present in definite numbers per cell unit, may then appear in double, triple, or quadruple sets.

The cause of these internal changes under natural conditions is still under dispute; a number of different influences are at work, any one of which may be responsible. It has been possible, however, to produce identical results artificially by treating germinating seeds with a chemical called colchicine, which is derived from the autumn crocus (*Colchicum*), or with podophylline, extracted from the May apple (*Podophyllum*). An ever-increasing number of improved ornamental plants, some with giant flowers, which have been produced by means of such treatments, are offered by commercial seedsmen.

COLCHICINE AND PODOPHYLLINE. What is significant is the fact that the chemical compound used in these experiments is a pure plant product (now produced synthetically), which, by the way, is contained not only in *Colchicum* but likewise in various other members of the same plant family (Liliaceae). That colchicine is most effective on germinating seeds is particularly intriguing, since under natural conditions seeds germinate in soil. How and why is colchicine produced in certain plants only? What becomes of the colchicine when the plants containing it die and decompose? So far this is unknown, and neither colchicine nor any other compounds with similar effects have as yet been extracted from soils where they must be present only in very minute quantities.

INFLUENCE OF X RAYS AND OTHER RAYS ON GENES. Other experiments, which have used X rays as well as other types of radiation in efforts to cause changes in plants, are worth considering also, since they have succeeded, at least in part, with such plants as tomatoes and cotton. The most notable results were obtained with fruit flies. It appears that X-ray treatments do not affect cell division or the chromosomes themselves, in the manner of colchicine, but rather affect the genes (page 41), which may be rearranged into new combinations within the chromosome. It is assumed that even the atoms of which the genes are composed may change places with each other, somewhat in the manner of the ions which change places in ion exchange (page 75). This has not been seen by anybody so far, since no existing microscope is powerful enough to show it, but the results obtained can hardly be explained in any other manner. In fact, all interpretations of such results are based on the definite assumption that genes and the still smaller particles or atoms, of which they are composed, do actually exist.

Radiation from Soil. In this atomic age it is generally known that many minerals produce radiation, some powerful, some hardly perceptible. Therefore, the speculation that radiation from soil minerals or mineral soils, or perhaps from the mineral matrix underlying certain soils, may likewise cause changes in plants does not appear to be too far fetched, if one considers the above outlined experiments with X rays and other rays.

Actually, it has been found (Kotval and Grey, 1947) that certain decomposition products from various always-present radioactive minerals —such as thorium, uranium, and actinium—emit alpha rays of sufficient intensity to cause mutation in plants. The nitrate salt of uranium, for instance, has, in scientific experiments, caused hereditary changes in various kinds of fungi. It was established that cosmic rays are too weak to have any influence, and that the gamma rays, emitted by the above-mentioned elements themselves, are ineffective, because the elements are usually too widely dispersed and are present in too minute amounts. The gaseous radon, however, which is one of the decomposition products of radioactive minerals, emits rather powerful alpha rays, more effective than X rays, and has been found in the soil solution and in the soil atmosphere in sufficiently high concentrations. Storage of seeds also has resulted in chromosome aberrations, which have been explained as being due to the accumulative action of radiation from radioactive material contained in the seeds.

As yet, the available proof is not absolutely conclusive, and much more work must yet be done on this subject, but certain strange natural phenomena are very hard to explain, unless one accepts the influence of soil-mineral radiation. It is a fact that in certain strictly delimited regions, plants, which elsewhere show no inclination to variation, produce a great multitude of odd forms.

As an example may be cited the wake-robin (*Trillium grandiflorum*), which occurs by the millions over a very large part of eastern North America and which everywhere is quite uniform in appearance, showing extremely little variation. In a few isolated sections of woodland located in different sections of the country, however, it produces, without reasons anyone has so far been able to discover, a great abundance of different types, including doubling of the flowers in varying degrees, green flowers, striped flowers, and double sets of leaf whorls. It can be expected that future investigations will provide an answer to this puzzle. It may be that alpha rays emitted by radioactive soil constituents as well as by living plant tissue may play a much more important role in the origin of species than is realized at present.

The fact that plant mutation is not infrequently localized in this manner does not by any means imply the presence of exploitable quantities of radioactive minerals. A very minor increase of concentration above average, and perhaps local soil conditions favoring the accumulation of radon or similar decomposition products, is sufficient to account for such effects.

MUSTARD OIL CAUSING MUTATION. Still more closely in line with this investigation of soil organic matter is the recent observation that mustard oil (allyl isothiocyanate) induces gene mutations in fruit flies in a manner very similar to a heavy dose of X rays. The fact that this chemical substance is known to occur naturally in various species of the genus *Brassica,* such as wild mustard, black mustard, rape, and others, is particularly intriguing. Since these plants are common cosmopolitan weeds, their remains are sure to be frequently present in soil organic matter. So far, however, no actual proof is available that the minute doses of mustard oil, which thus may become incorporated in the soil, have an influence on other plants or, perhaps, on their germinating seeds.

COUMARIN AND DICOUMAROL

Before closing this discussion of organic matter, one more substance may be considered which actually has nothing to do with soil, though soil frequently is blamed for the effects it causes. In fact, the completely unfounded and even ridiculous claim is made repeatedly that artificial fertilizers are responsible for these effects.

This substance is coumarin, which is present in many plants and which apparently serves as a growth regulator. Many grasses, in particular, contain it, and it gives the pleasantly sweet fragrance to new-mown hay. In itself, coumarin is harmless, but if hay, especially sweet-clover hay, spoils through improper curing, a new group of substances is formed which is designated by the general term *dicoumarol.* These substances have the ability to prevent blood from clotting—as it normally does as soon as the skin is broken—and, if spoiled sweet-clover hay is fed to cattle, serious hemorrhages, ending with death, frequently result. This sweet-clover disease of cattle is easily preventable through proper treatment of the hay. As previously pointed out, this phenomenon has nothing to do with soil. It is mentioned here in connection with humus only because humus fanatics are wont to quote it as an argument against the use of artificial fertilizers.

New varieties of sweet clover with very low coumarin content have been bred recently. Their use will largely eliminate the danger of dicoumarol formation when such hay is improperly cured.

Dicoumarol is now produced synthetically in considerable quantities and serves medicinally as a valuable agent in the prevention of blood clotting, for instance in thrombosis (an illness in which blood clots are likely to form within a blood vessel and may thus cause sudden death).

Warfarin, the famous rat poison, likewise is a synthetic coumarin compound. It kills rats by causing fatal internal hemorrhages. In addition, warfarin is used also very effectively as an antiblood-clotting medicine in humans.

POISONOUS HUMUS

The many valuable properties of humus and the great importance of soil organic matter for healthy plant development have been made evident. It is necessary, however, to add that there also is such a thing as dangerous and potentially poisonous humus, a fact which is not widely known. This develops when selenium-containing weeds are added to the compost pile. Since selenium can be absorbed by most crop plants in health-endangering quantities only after it has been converted into assimilable form by certain weed plants, this is a very real menace which must not be overlooked wherever selenium occurs in higher than average concentrations (page 23).

4. SOIL MICROORGANISMS AND OTHER SOIL INHABITANTS

The teeming billions of microorganisms (also called microbes) and other living organisms which inhabit soils are not soil constituents, but, being an integral and indispensable part of all fertile soils, they seem to belong in this part of the book where fundamentals are considered. There can be no doubt that their importance as far as plant growth is concerned ranks fully equal to the mineral and organic soil contents discussed in the preceding chapters. Higher plants cannot utilize the various elements in complex organic form or as raw minerals. The former have to be broken down into simple inorganic or mineral materials, and the latter have to be made soluble. The soil inhabitants constitute a required link in many of these processes, and their aid is invaluable.

SOIL MICROBES

General Role

The processes involved in the decomposition of organic matter, with the accompanying formation of new compounds, are popularly referred to as putrefaction, fermentation, and decay. In more exact scientific terms, the four main processes involved are oxidation, reduction, hydrolysis, and carbonation. (See Part III.) By whatever name they are called, these processes are of immense importance, since, without the microbes, organic matter would accumulate until all the combined nitrogen, phosphorus, potassium, sulfur, and carbon would be locked up unavailably either in organic form or as rock or gas. If microbes did not continuously liberate these important elements from the organic matter, turning them back into circulation so that they can be used over and over again, plant and animal life would soon cease because of the exhaustion of available elements. (See Chapters 18, 22, and 24.)

An enormous variety of types of microbes inhabit the soil. They vary considerably, not always very much in appearance but very decisively in their living habits and in the processes for which they are responsible. The individuals are so small that they cannot be seen with the naked eye and can be studied only under powerful microscopes. Their number is legion.

Sizes and Numbers

An excellent idea of the vastness of numbers involved as well as of the minuteness of these organisms is conveyed by Waksman and Starkey in "The Soil and the Microbe." Speaking of bacteria, which usually are most numerous in the soil, the authors state that bacteria are so small that 500 to 1,000 placed in line, end to end, would extend only to 1 mm; 1 million to 1 billion of them would weigh no more than 1/1,000 g, and even then this mass of cell material would consist of 80 to 85 per cent of water. It is not exceptional to find hundreds of millions of bacteria in 1 g of soil, yet even that number would occupy only one ten thousandth of the total volume of the soil. That is the reason why these large numbers remain unnoticed. Actually, it takes a highly specialized technique and careful search to reveal them.

Factors Governing Microbial Activity

The extent of the activity of the soil microbes is limited only by the supply of available energy, by environmental conditions, and sometimes by the formation of certain substances which are detrimental to their development. The activity and development of the micro soil population is affected in particular by the supply of oxygen, the presence of organic matter, the availability of inorganic compounds, the temperature, the physical condition, the moisture content, and the reaction (pH) of the soil. When considering the undeniably great importance of the processes for which the soil organisms are responsible, the factors which have just been enumerated become highly significant, because they may be decisively influenced by soil management.

Most of the microbes which inhabit the soil are useful, but some are, or may become, harmful as far as plant culture is concerned. Soil treatment, therefore, must be directed toward reducing injurious effects to a minimum and increasing useful activity to a maximum. In other words, one must consider in all soil treatment not only the higher plants, which are of immediate concern, but also the response which may be expected from the soil microorganisms. In this manner only can a healthy living soil and a vigorous plant development be established and maintained. Further details on this subject will be found in Part III.

For all the reasons given, it is worth while to know at least something about soil microorganisms. Because of the vast variety involved, some of them still incompletely known, it is impossible to go into details. The following discussion, therefore, is restricted to the most important groups. Some other soil dwellers which are visible to the naked eye are discussed at the end.

PLANT MICROORGANISMS

Microscopic Algae

These extremely simple plants, which stand very low in the taxonomic scale, are present in nearly all soils in considerable numbers. They always contain chlorophyll as well as various other pigments, such as phytocyanin, carotene, and xanthophyll, and are green, blue-green, violet, or brown in color. Because they contain chlorophyll, they can synthesize their own organic matter from inorganic materials as long as they have light and moisture. (See photosynthesis, page 100.) For this reason, they are usually found at or near the surface of the soil. They are capable of surviving prolonged drought, becoming active again quickly as soon as soil moisture content increases. Their main role may be said to consist in the accumulation of organic matter in raw inorganic soils.

Microscopic Fungi

Fungi depend upon the presence of soil organic matter. Since they are devoid of chlorophyll, they cannot, like the algae, obtain their carbon from the carbon dioxide of the air. Because they do not require light, fungi can penetrate rather deeply into the soil, provided that moisture conditions are favorable. They have been found abundantly at depths of many feet below the surface.

Classification of Fungi. Soil fungi have been divided into seven groups, as follows: (1) those which grow on practically pure humus; (2) those which grow on soil containing more or less organic matter; (3) those which grow on manure; (4) those which grow below the surface of the soil; (5) those which grow on the lignin of decomposing plant materials; (6) Mycorhizal füngi, wound parasites, and occasional parasites; and (7) true parasites.

Fungi develop quite well over a wide range of pH (2.5 to 9 or even

11), but in soils near the neutral point of pH, the bacteria, which there develop in greatest numbers, provide such strong competition that fungi are partly suppressed. Since fungi have considerable resistance to acidity —much more than all other microorganisms—it is not surprising that they occur in greatest abundance in the pH range 4 to 6. Inhibition of the germination of fungus spores becomes evident only at pH 1.5 to 2.5. Though fungi generally are present in the soil in much smaller numbers than are bacteria, their mycelia develop so extensively that the total amount of organic matter produced is considerably greater. Like the algae, they must, therefore, be considered as a potential source of organic soil matter. Their role in the decomposition of organic matter, which results in making various nutrients available to higher plants, is mentioned again in Part III (page 165). The activities and functions of the mycorhizal fungi, which are treated here in somewhat greater detail, are very similar to soil fungi in general and may serve as an indication of their significance.

MYCORHIZAL FUNGI. These fungi are of particular interest because of their direct interaction with living higher plants. They serve to emphasize the delicate balance between soil and plants which exists in nature and which must be considered in all efforts at plant culture. *Mycorhiza,* or fungus root, is very widespread in nature and is probably the rule rather than the exception.

Under ideal conditions a true symbiosis is formed, in which both the fungus and the higher plant benefit equally. The fungus obtains carbohydrates and probably other food materials from the root cells which it penetrates. The higher plant gains an advantage from having difficultly soluble organic substances, which it could not utilize, transformed by the fungus, which is able to decompose them and to change them into readily available inorganic compounds. This results in increasing the concentration of soluble substances in the immediate vicinity of the roots. Under certain conditions, and especially with young seedlings, the fungus may even take on the function of root hairs. Water, inorganic nutrients, and organic substances absorbed by the fungus may become available to the plant either directly, from the penetrating parts of the fungus, or indirectly, through the digestion of the fungus mycelium, which takes place within the penetrated cells. Seeds of orchids and various Ericaceae are known to require, under natural conditions, the presence of mycorhizae for germination. The production of auxins—growth-promoting substances —by the mycorhizal fungi is undoubtedly of particular significance.

It appears that the nitrogen which the fungi make available from raw organic matter is particularly significant, and it may be mainly for this reason that in raw humus soils—such as those frequently inhabited by various conifers (spruces, firs, and hemlocks) as well as by many Ericaceae—mycorhizae are absolutely essential for the healthy development of higher plants.

As far as forest trees are concerned, it has been generally observed that mycorhizae are most abundant and most active in poor soils or in soils with a low availability of nitrogen, phosphorus, potassium, or calcium. Some instances are known also in which nitrogen did not seem to be involved at all, and only the uptake of phosphorus and potassium was definitely favored by the mycorhizal fungi.

Effectiveness of Mycorhiza. The effectiveness of such a symbiosis depends upon an equilibrium between the invading power of the fungus and the resisting power of the host. As soon as either of them gains the upper hand, because of conditions which favor its development, the other suffers or is killed. This means that when a plant, which habitually is associated with a root fungus, is cultivated under unfavorable soil conditions, for instance when an erica or a rhododendron is planted in a soil which is lacking in organic matter, the mycorhiza is likely to turn into a parasite, harming the plant. This example shows very clearly that it is not sufficient to acidify a soil, perhaps through addition of sulfur or of aluminum sulfate, where rhododendrons or azaleas are to be planted, but that humus must likewise be provided.

Another side light on cultural procedures is provided by the fact that all root fungi are very sensitive to sunlight and to lack of moisture. This is why conifers are generally transplanted with a ball of earth attached to them, or at least with their roots wrapped in a moist piece of burlap. To dig up a spruce tree in the woods, transporting it with bare, uncovered roots, results nearly always in the death of the plant.

The most favorable soil reaction for mycorhizae is pH 4 to 5. The development of root fungi is very poor above pH 6.5 and below 3.5.

Actinomyces

Actinomyces (ray fungi) is a genus usually classified as intermediate between fungi and bacteria, since the organisms show certain similarities to both, and they are frequently looked upon as the common ancestral form of these two groups. The actinomyces, with few exceptions, are even more sensitive to acids than most bacteria and generally find optimum growth conditions between pH 7 and 8.5, though some of them thrive even above pH 9. Only a few (*Actinomyces acidophilus*) live under acid conditions with an optimum at pH 4 to 5. The fact that these organisms, which are very active in the decomposition of organic matter—nitrogenous as well as nonnitrogenous—are also exceptionally resistant to drying renders them valuable as humus producers in arid alkaline soils. Some of the actinomyces are capable of decomposing cellulose very rapidly. Liming and draining of swampy soils favors the development of actinomyces, which results in the decomposition of the soil organic matter and contributes significantly to the favorable effects on plant growth.

That the sensitivity of most actinomyces to acidity may be used to suppress some of them which are parasitic and cause plant diseases—for instance potato scab—is mentioned on page 111.

Bacteria

The largest number of all soil microorganisms belong to the immensely diversified group, bacteria. Their variety is so great that a taxonomic classification, even of only those bacteria which are known to occur in the soil, would be far beyond the scope of this book. The student of soils will be most interested in the physiological activity of these organisms as far as this influences the fertility of the soil and therewith the development of crop plants.

Bacteria Classified According to Energy Sources. According to their actions and modes of life, bacteria may be divided roughly into groups as follows: (1) Bacteria which obtain the carbon they require for their life cycle from the carbon dioxide (CO_2) of the soil atmosphere and their energy from the oxidation of inorganic substances or simple compounds of carbon (autotrophic bacteria). Some of these utilize simple nitrogen compounds, others hydrogen compounds, still others sulfur, iron, and manganese compounds. Some are able even to assimilate elemental sulfur.

(2) Bacteria which obtain their carbon and energy from soil organic matter (heterotrophic bacteria). Among these are (a) those which are able to utilize and to fix the gaseous nitrogen of the soil atmosphere or of the air, and (b) those which require nitrogen in combined organic or inorganic form. The last group is of considerable importance because of its service in the breakdown of complex organic compounds. Some of the bacteria belonging here are involved in the process known as *ammonification.* The denitrifying bacteria, which liberate gaseous nitrogen into the air, also belong in this group.

AEROBIC AND ANAEROBIC BACTERIA. Some of the bacteria from all these groups require free gaseous oxygen (aerobic bacteria), whereas others either can get along without it (facultative anaerobic bacteria) or cannot even live for more than a very short time in the presence of free oxygen (obligatory anaerobic bacteria). The interaction of aerobic and anaerobic bacteria is of considerable importance in the dynamic soil processes and is discussed in Part III (page 165).

The numerous processes brought about by soil bacteria are usually interdependent and follow one another, which means that a reaction initiated by one type of bacterium is frequently utilized and continued by another. The substances produced, many of them valuable as nutrients for higher plants, are, in many instances, actually waste products of the metabolism of the bacteria.

The following details concerning some of the most important activities of bacteria from the above groups should be of interest to the student of soils.

GROUP 1. **Nitrifying Bacteria, Sulfur and Iron Bacteria.** These bacteria, which do not require organic nutrients for structure or for energy, are usually even incapable of decomposing organic matter. The very fact, however, that they live on strictly mineral media which they oxidize, while they utilize the carbon dioxide of the air or of the soil atmosphere for their body development, renders them of considerable importance as builders of organic substance in mineral soils.

The nitrifying bacteria, such as *Nitrosomonas,* which transforms ammonia into nitrite, and *Nitrobacter,* which changes nitrite into nitrate, are particularly important, since they are the ones that must maintain the nitrate supply of higher plants.[1] Other bacteria of this group assimilate elemental sulfur and in this manner cause acidification of alkaline soils. Those which utilize simple sulfur compounds, such as hydrogen sulfide, ammonium sulfate, or gypsum (calcium sulfate), serve as an important source of sulfur for higher plants (see page 229). The bacteria which precipitate, accumulate, or dissolve iron in the form of various iron salts may frequently be observed with the naked eye as a brown scum, floating on puddles in marshy ground or on the border of small rivulets running through a bog. In wells or in water pipes coming from wells they occasionally grow so luxuriantly that water flow is completely blocked. (See page 239.)

GROUP 2, a. **Nitrogen-Fixing Bacteria.** All higher plants and all ani-

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[1] It has been established that certain heterotrophic soil organisms, bacteria as well as at least some actinomycetes, are able to produce nitrite from various organic compounds. [Quastel, J. H., Scholefield, P. G., and Stevenson, J. W., *Nature,* **166,** 940 (1950); Jensen, H. L., *J. Gen. Microbiol.,* **5,** 360 (1951); Isenberg, I. H., *et al., Bacteriol. Proc. Soc. Am. Bacteriologists, Abstract,* p. 41, annual meeting (1952); Fisher, W. P., *J. Bacteriol.,* **64,** 596 (1952); Hutton, W. E., and Zobell, C. E., *J. Bacteriol.,* **65,** 216 (1953).]

It has now been found that, in laboratory culture at least, one soil fungus (*Aspergillus flavus*) is able to produce not only nitrite but also nitrate from ammonium nitrogen [Schmidt, E. L., *Science,* **119,** 187 (1954)]. It is to be expected that other soil fungi can do the same, but it is still unknown how important their contribution is to the economy of the soil.

mals, as well as most of the microorganisms, require nitrogen in considerable quantities, but they can assimilate it only in combined form as organic or inorganic compounds. The large amounts of elemental gaseous nitrogen contained in the air are unavailable to them. Very great demands, therefore, are made continuously on the nitrogen compounds contained in the soil, especially where crops are raised, and even the application of manure and artificial fertilizer can seldom do more than supply the immediate needs of the growing plants. It is for these reasons that the ability of certain bacteria to assimilate and to fix the gaseous nitrogen of the air or of the soil atmosphere assumes very great importance.

The two main groups of nitrogen-fixing bacteria are those which live free in the soil (*Azotobacter, Clostridium,* and others) and those which live in symbiosis with higher plants (*Bacillus radicicola* and others). The bacteria of both groups, however, are able to utilize nitrogen from organic or inorganic compounds also.

Free-Living Nitrogen-Fixing Bacteria. The most important bacteria of this group are the species of *Azotobacter* which are omnipresent in all soils with a reaction above pH 6. Since they are rather sensitive to acidity, they are absent in more acid soils but will appear and become active as soon as the pH is raised sufficiently through liming. The importance of these organisms is such that it has even been proposed to use the numbers of azotobacter present in a given soil as an index of soil fertility. The fact that species of *Azotobacter* are among the first organisms which develop in newly formed soils is discussed on page 201.

Nodule-Forming Nitrogen-Fixing Bacteria. The nitrogen-fixing bacteria are the ones which cause the formation of small nodules on the roots of most legumes (such as clover, alfalfa, beans, and peas). Though it has been known for many hundreds of years that the plowing under of various Leguminosae raised the fertility of the soil, the little tubercules or nodules on their roots were not observed and described until the fourteenth and fifteenth centuries. Not until 1887 (Hellriegel and Willfarth) was it proved that the root nodules contain colonies of bacteria, which live in symbiosis with their host plants and which make the atmospheric nitrogen available to them. The most common of these nodule bacteria is *Bacillus radicicola.* This and its relatives are active over a considerable range of temperature (37°F to well over 100°F) but are influenced markedly by the pH of the soil. Their limits of tolerance are between pH 4 and 9 or 10, depending upon the type of the host plant, the variety of the bacterium involved, and the physical condition of the soil. Below pH 5, nodule formation is usually limited. (See also Chapter 18, page 200.) A number of other plants besides the Leguminosae, such as

Ceanothus (redroot), *Elaeagnus* (silverberry), *Alnus* (alder), and *Myrica* (sweet gale), are known to have bacterial root nodules.

Certain tropical plants show an even more intimate symbiosis with nitrogen-fixing bacteria, which live in the intercellular spaces of their hosts leaves and are frequently found throughout the plant, occasionally forming nodules on the leaves. They even enter the seeds (between the embryo and endosperm) and, in this manner, are passed on to the young seedling plants, establishing a sort of hereditary symbiosis.

GROUP 2, b. Here belong the largest number and variety of all the soil bacteria, so many in fact that it is not possible to give here more than a very general outline based on their specific actions. In the passage treating of the organic constituents of the soil (page 28), the various organic substances were enumerated, which, through bacterial decomposition, become humus. The descriptions in the following four sections are based on the same four divisions.

Decomposition of Carbohydrates. The largest part of the plant matter which decomposes in the soil consists of cellulose. This is broken down by numerous bacteria, and the end products of the decomposition are mainly various gases, such as hydrogen, carbon dioxide, and methane, as well as certain organic acids such as formic, acetic, propionic, and butyric acid, and certain types of alcohol.

Cellulose decomposition proceeds most rapidly in the presence of sufficient supplies of nitrogen and phosphate. The addition of slowly dissolving lime (ground limestone) helps by neutralizing the acids, which are waste products of the metabolism of the bacteria and which actually hinder their further development. Most of the denitrifying bacteria, which liberate gaseous nitrogen into the atmosphere, are cellulose decomposers and are active under anaerobic conditions.[2]

Decomposition of Lignin. Lignin is the noncarbohydrate portion of lignified plant tissue. In fact, next to cellulose it is the most abundant constituent of plant tissue. For this reason, it is commonly present in soils and, since it is highly resistant to decomposition, is of particular interest. Since lignin and the formation of humic acid are discussed in further detail in Part III (page 167), however, no discussion will be included here.

Decomposition of Proteins. Most of the nitrogen added to the soil in organic form, whether as stable manure, green manure, cottonseed meal, tankage, bone meal, dried blood, or fish meal, is in the form of proteins. Such substances cannot be utilized directly by higher plants and must first be decomposed and broken down into simpler compounds through

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[2] For further details, consult Waksman, S. A., "Soil Microbiology," New York, John Wiley & Sons, Inc., 1952.

the agency of microorganisms. The biological processes involved in the decomposition of proteins are usually popularly called *putrefaction* and *decay*. These processes are quite complex, since many different types of bacteria take part in them, and one group of organisms usually acts upon the products formed by another. No attempt will, therefore, be made here to name any of the very wide variety of bacteria which would have to be considered.

It may suffice to state that the most important end product which results is ammonia, but various other substances, such as hydrogen sulfide, amino acids, and other acids, as well as derivates of indol and skatol (especially indol acetic acid), are formed also. (See Chapter 18.)

Decomposition of Various Fats, Waxes, and Resins. Fats, waxes, and resins can be extracted from most soils. Since the amounts present in a given soil remain fairly constant from year to year, while at the same time it is known that certain microorganisms themselves synthesize fats and therewith add to the supply, it is evident that these substances are continuously, though slowly, decomposed. The fats are first hydrolized (this proceeds only in moist soils and mainly through the action of fungi) into glycerol and various alcohols which are readily utilized by various bacteria as sources of energy. The fatty acids which are formed are decomposed further.

One of the end products of fat decomposition is dihydroxystearic acid, which, if it were to accumulate, would have toxic effects on higher plants. Under normal conditions of cultivation, however, including plowing, drainage, liming, and manuring, such a toxic accumulation of dihydroxystearic acid cannot occur, since this acid is decomposed almost as quickly as it is formed.

Production of Water-Repellent Mineral Soaps. Since fatty acids are likely to be produced in all processes of protein decomposition, another phenomenon, for which these acids are responsible, may be mentioned in this connection. When an abundance of magnesium or calcium is present, or when magnesium or calcium fertilizer is added to soils containing fatty acids, water-insoluble mineral soaps are formed. When such a soil is allowed to become dry, it does not absorb water anymore, and irrigation water runs off without wetting, as if the soil were covered with oil.

This phenomenon, which may have serious consequences, has been observed in particular in the citrus-growing areas of Florida, where clayey soils are involved. It occurs also, however, with certain peaty bog soils, which, through deposits from water, sometimes contain rather high amounts of magnesium as well as of calcium sulfate. Such soils likewise are very difficult to moisten again, once they have become dry. Unfortunately, this type of soil is not infrequently sold commercially to top-dress lawns and flower beds, for which purpose it is completely unsuitable.

It may be possible to correct this highly undesirable condition through the application of certain detergents which would dissolve the mineral soaps. This possibility does not appear to have been investigated, however, and little is known about the effect a detergent might have on other soil properties as well as on higher plants.

ANIMAL MICROORGANISMS

Protozoa

Protozoa are unicellular but are classed as animals because of their mode of life and their metabolism. There is a large variety of them, and, though the majority are microscopic in size, some may become as large as 4 to 5 mm in diameter. Some also form colonies of numerous individuals. They are most common in moist, fertile soils, where they swim about freely in the soil solution. Their pH preference varies with the variety, from pH 4 to 8 or even above 9. Most of them live on bacteria or other soil microorganisms, some devour their own kind, others are omnivorous, and still others live on soluble organic substances. It was formerly believed that, because they live largely on bacteria, the protozoa served to maintain a sort of biological balance in the soil. Investigations tend to show, however, that the protozoa do not appreciably limit bacterial development. The group as a whole cannot be said to have either a good or a bad influence on soil fertility.

The rather high sensitivity of protozoa to heat has led to a speculation which appears to be erroneous. Partial sterilization of soil by steam or dry heat is always followed shortly by a readily determinable rise of available nitrogen in soil content. It was assumed that the destruction of the protozoa, freeing the bacteria of their predators, was responsible. The number of protozoa present in the average soil, however, is always relatively small, and partial sterilization actually does not destroy them all. It is now generally agreed that the killing of most fungi and insects has a much greater influence. This results in making large amounts of readily decomposable organic matter available to the surviving bacteria, enabling the latter to multiply rapidly and to liberate large amounts of nitrogen as ammonia.

Rotatoria or Rotifers

These are minute, mostly microscopic, animals which live generally in swamps and marshes or in mosses and moist forest leafmold. No real study concerning their significance in soil fertility appears to have been made.

SOIL ORGANISMS DISTINGUISHABLE WITH THE NAKED EYE

Higher Fungi

The higher fungi are commonly known as mushrooms and toadstools. They live on decaying wood or in moist soils, which are rich in organic matter, and their aid in the decomposition of cellulose-containing plant parts, such as wood, leaves, and conifer needles, is significant. As far as soil fertility is concerned, they must be considered of minor importance.

Eelworms

Nematodes or eelworms are threadlike, or spindle-shaped, almost transparent animals without close relation to other types of worms. Several thousand species of them have been described, which vary greatly in size. Many are so small that they can be seen only under magnification, but some may reach a length of ¾ in. Their eggs and, in some species even the adult animals, are very resistant to drying, being able to remain dormant for many years—in one recorded instance as long as 39 years—and to revive when conditions become favorable again.

Many nematodes are parasites, some of animals or man, and others live in water, even in the salt water of the sea. Of the large numbers which inhabit soils—apparently all types of soils under all kinds of conditions—most are harmless. Some are beneficial by feeding on harmful nematodes or by assisting in the decomposition of organic matter. Several hundred species, however, are known to feed on living plants, especially on plant roots, and frequently do very serious damage.[3] The root injury caused by the nematodes results in lowered efficiency in the transport of water and nutrients to the plants, with the consequence that infested plants usually show, by their appearance, a lack of water or fertilizer, in spite of both being present in sufficient amounts. In addition, the wounds made by the nematodes provide entry for various fungi or bacteria, frequently causing rotting of the invaded tissues. The serious threat to the cultivation of black pepper in Indochina provides an example of such a combined assault by nematodes and rot-inducing fungi. During a 10-year period (1941 to 1951) the total crop was reduced by two thirds.[4] The higher incidence of fusarium wilt of cotton in heavily nematode-

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[3] Taylor, A. L., "The Tiny but Destructive Nematodes," pp. 78–82, in "Yearbook," Washington, D.C., U.S. Department of Agriculture, 1953.

[4] Barat, H., "Etude sur le dépérissement des poivrières en Indochine," Arch. Rech. Agron. Cambodge, Laos, Vietnam, 13, 92 pp., 118 illustr. (1952). This is a 92 page booklet, published by the government of Vietnam as No. 13 of a series called ARCHIVE DES RECHERCHES AGRONOMIQUES.

infested Louisiana soils is another case in point. As far as is known at present, no crop or ornamental plant is safe against nematode attack. Fortunately, several chemicals are now available which make it possible to control soil nematodes, and, since the damage caused is widespread and serious, this development must be considered a very important advance in soil treatment.

Earthworms

Earthworms, so common in the soil that everyone has seen them, have recently received a large amount of attention and publicity, and their importance has frequently been discussed or disputed in magazine articles.

The first man to call attention to the earthworms as agents in soil fertility was Charles Darwin, who studied them for many years and who, in 1881, published his now classical paper "The Formation of Vegetable Mould Through the Action of Worms with Observations on Their Habits." Darwin observed that the earthworms pass fine organic and mineral particles, gathered in the lower soil layers, through their digestive tracts and deposit them on the surface as "castings," which are rich in plant nutrients. These castings were computed to amount to the astonishing quantity of 6 to 20 tons/acre/year. This has been confirmed by recent investigations.

There can be no doubt that this activity of earthworms is significant as far as soil fertility is concerned. In forest soils earthworms fulfill the important function of carrying the accumulating organic matter from the surface into the lower soil layers and of later bringing it back again in their castings, thus producing a favorable mixture. The extensive tunneling of the earthworms is an important factor in aeration and the movement of soil water.

In lawns, show gardens, and on the putting greens of golf courses, earthworms are usually considered to be distinctly undesirable and are destroyed with arsenate of lead. With potted plants, earthworms likewise are undesirable, since they tend to gather at the bottom of the pot and to block the drainage hole with their castings.

Earthworms have been observed as deep as 40 in. below the surface, though 1 to 2 ft is a more usual depth for them. The soil pH has a considerable influence on earthworms. They occur in the range between 5.6 and 8.3 but are most abundant between pH 7 and 7.8. Acid soils do not contain any earthworms.

It is frequently claimed that application of artificial fertilizers, especially of those containing ammonium sulfate, are harmful to earthworms and are therefore undesirable. Ammonium sulfate actually is transformed in the soil into nitrate, through the activity of nitrifying bacteria, and, in the absence of calcium in poorly buffered sandy soils, this reaction may result in a lowering of the pH to below 6. As was shown above, such an acid soil is unfavorable for earthworms and within these limitations the above claim is correct. Application of ammonium sulfate, however, is customarily accompanied by liming, which completely counteracts the acidifying action of the ammonium salt. Other fertilizers which do not acidify the soil have no effect on earthworms.

There is no scientifically supported evidence for the claim, made occasionally, that artificial introduction of cultivated earthworms into a soil will produce almost miraculously beneficial results. The facts are that any increase in organic-matter content of a soil will, by itself, result in an increase of the earthworm population as long as conditions otherwise are favorable. Under unfavorable conditions or when a soil has a very low organic-matter content, artificially introduced earthworms will either die or move elsewhere. For these reasons, it remains most doubtful whether they will ever become the general aid in horticulture for which they sometimes are recommended.

Wood Mites

The Oribatidae—often called wood mites—belong to the order Acarina, which contains many pests of plants as well as of man and beast. The wood mites, however, live strictly on decaying organic matter, and in this manner they contribute materially to the reduction of raw organic matter to humus. They are so small that they often escape notice altogether, but they are present in large numbers in most soils. As many as 12,200 have been counted in 1 sq yd of cultivated soil to a depth of 4 in. Several hundred species have so far been distinguished, and, since these are rather selective in their habitat, their study has been found to be a valuable aid in the understanding of soil biological processes, especially in forest economy. Certain ecological factors, such as the degree of humidity and the pH value of the soil, limit the distribution of the various species, so that by their presence or absence, respectively, the dominance of certain species can actually be used as indicators of soil condition.[5]

Insects

Insects are important, since they are extremely numerous and since very many of them spend one or more stages of their development in the

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[5] Strenzke, K., "Die Oribatiden und ihre Synusien in den Böden Norddeutschlands" Zoologica, Band 37, Heft 104, Stuttgart (1952). This is an article in a periodical, called Zoologica, and appeared in Vol. 37, No. 104, p. 1–172.

soil. It has been estimated that more than 90 per cent of all insects do so. Millions of insects are often present in 1 acre of land.

In general, pasture land contains many more insects than cultivated land, the reason being that under pasture conditions the continuous soil cover serves as a protection, whereas soil cultivation brings the insects to the surface, exposing them to the weather and to birds. Application of manure tends to increase the soil insect population, not only because many insects live on decomposing organic matter, but also because of the loosening effect the latter has on the soil structure, which facilitates penetration.

A great many soil insects are harmless as far as plant development is concerned, but a large number of others cause considerable damage. How to control harmful soil insects through soil treatment or methods of tillage cannot be included within the framework of this book.

Springtails. One type of insect may be singled out because it is frequently overlooked but, as recent investigations have revealed, is of specific interest. The springtails are extremely small insects of the order Collembola. They have been given the name "springtails" because of their ability to jump by means of caudal appendages which look like a tail. These they can fold under their bodies and then straighten suddenly, precipitating themselves into the air. They are very numerous, over 24,000 having been counted in a square yard of soil to a depth of 4 in. (Only 140 earthworms were present in this same amount of soil.) Like the wood mites, they normally feed on decaying organic matter, which makes them useful in the household of nature. Unlike the wood mites, however, they may become harmful when they are introduced with the soil into plant cultures. Under favorable conditions, such as are offered by a hotbed where ample organic matter is present, they multiply very rapidly and will then feed also on bulbs, tubers, and roots, as well as on young shoots, thereby doing serious damage. Soil sterilization is the only remedy.

CONCLUSION

Although a considerable variety of small animals, in addition to those mentioned, live in the soil, such as certain crustaceans, ticks, spiders, millepedes, snails, and slugs, they are of rather minor importance.

The various groups of organisms inhabiting the soil normally establish some sort of an equilibrium among themselves; at least, they constantly strive toward such an equilibrium, which—being influenced by temperature and moisture—varies with the season. Most striking is the equilibrium established between the morphological groups of bacteria, which always shows a dominance of certain groups, with others definitely in the minority. This equilibrium is surprisingly uniform throughout the soil mass.

The Rhizosphere

Very significant is the fact that in the immediate vicinity of plant roots—the so-called "rhizosphere"—the above-mentioned equilibrium varies distinctively with different types of crop plants as well as with different types of soil, sometimes favoring one and sometimes another group of bacteria and fungi.[6]

Plant-root excretions, consisting of sugars, vitamins, amino acids, and other organic compounds, are generally considered to be responsible for the much greater density of the micro population in the rhizosphere than in the general soil mass. The majority of the bacteria, actinomyces, and fungi increase about 10 times in the rhizosphere. Ammonifying and denitrifying bacteria may increase as much as 100 times. *Azotobacter* increases in the rhizosphere only in soils with low organic-matter content, but it appears that the turnover of the population is faster in the rhizosphere than elsewhere in the soil, meaning that the nitrogen assimilated by this organism from the air becomes more quickly available. Bacteria which produce vitamins as well as those which are able to dissolve tricalcium phosphate are also more plentiful in the rhizosphere than in the general soil mass. Algae and protozoa do not increase appreciably in the rhizosphere (see also page 212).

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[6] Plant growth in relation to the bacterial equilibrium in soil, Lochhead, A. G., Transactions Royal Soc. Canada, Vol. 42, series 3, p. 73 (1948).

PART II

The Physical Condition of the Soil Contents and Their Properties as Related to Plants

INTRODUCTION

All the elements and their compounds which are present on the earth occur in three physically distinct states or phases. These are the solid, the liquid, and the gaseous phases. Not only do soils contain all three phases of many compounds, but the elements and their compounds change in the soil continually from one physical condition to another. This fact should be borne in mind throughout the rest of this text. Just as water may be present either as ice, as liquid, as vapor, or as all three together, any other compounds also are likely to change from the solid to the liquid and the gaseous state, or vice versa. It will be shown later what an important role water plays in these changes, not only as a solvent and carrier but also as an intermediary which induces a change in physical state. How chemical reactions and electrical attractions likewise interact in these processes has been indicated already in the preliminary discussion of organic colloids (page 29). The following chapters explain the technical details of these facts and are recommended for careful and concentrated reading. They are of very great importance, because a true conception of what goes on in the soil is impossible if these facts and their consequences are not fully understood.

Since it makes a great deal of difference to plants, as well as to the soil microorganisms, in which physical state the various soil constituents are present, the proportion of solid to liquid and gaseous substances prevailing in the average soil is rather significant. It is evident that, because of the wide variation in soil composition as well as in climatic, topographical, and geological conditions, this proportion likewise must be subject to considerable variation. Under average conditions and with a favorable amount of irrigation being assumed, however, the proportions in an average farm or garden soil can be expected to vary from 40 to 60 per cent solid, 20 to 35 per cent liquid, and 10 to 25 per cent gaseous components.

The three different types of soil components—the solid, the liquid, and the gaseous—representing mainly different physical conditions of the same elements or compounds, will now be considered separately (as far as it is possible to separate them) together with their characteristic properties.

5. THE SOLID SOIL PARTICLES

THE PORE SPACE

Liquids and gases, or vapors, are contained in the spaces between the soil particles and, since they are indispensable for plant nutrition, the spaces between the soil particles (called *pore spaces*) are just as important as the soil itself. Only the pore spaces make it possible for the plant roots to penetrate the soil and to seek out nourishment, which is the reason why nothing but algae, mosses, or lichens can live on a solid, homogeneous rock face. On the other hand, a large individual pore space (such as in coarse sand) is no more desirable for the development of plants than a very small pore space (such as in heavy clay). The reason for this is that the size of the pore space governs the capillarity of the soil water.

CAPILLARITY

The word "capillarity" comes from the Latin *capillus*—hair, and refers to the action of liquids which in hair-fine tubes—in this case represented by the pore spaces—are able to rise against the action of gravity, which pulls them downward. The energy responsible for this rising of liquids is called *surface tension* and need not be explained here. It is necessary only to bear in mind that the smaller the diameter of the tube (the finer the pore space) the higher the liquid is able to rise and the more persistently it is held through surface tension. This explains why clay soils, consisting of small particles with very fine pore spaces between them, are inclined to retain water and remain wet, whereas sandy soils, with much larger pore spaces, drain more readily.

This phenomenon of capillarity is of considerable importance, since the water—with all the various solutes it contains—which is held in this manner and thus is prevented from draining away down to the water table represents one of the main sources of supply for all higher plants. The water table itself is, under most conditions, too far below for water to rise from there to the surface of the soil through capillarity. Neither would this be desirable, since it would result in permanently wet soil. Under average conditions favorable for crop plants, the main resource is water from rain, melting snow, or irrigation, which is drawn into the soil by gravity and is held in the pore spaces by capillarity. Such capillary water does not keep the soil permanently wet but, rather, assists in making it friable, which renders the soil easier to cultivate. Further details on the action of capillary water as well as of water in general will be found in Chapter 7.

SOIL TEXTURE AND STRUCTURE

The size of the soil particles, large or small (coarse sand and heavy clay as extremes), determines the texture of a soil, and little can be done to change this texture except through admixture (as by adding sand or clay). The crumb structure of a soil is something quite different. Each crumb represents a composite or aggregate of many individual soil particles, and this soil condition is called *aggregation* (or granulation). Soil aggregation is a very desirable condition for plant growth because air and water can circulate freely through the pore spaces, which are of just the right size to allow surplus water to drain off and yet to retain ample reserves. Plant roots can penetrate without hindrance. The loose composite structure of the crumbs permits free interchange of ions (page 30) between the particles of the aggregate. Microorganisms find extremely favorable conditions for development in an aggregated soil.

The factors responsible for the development of soil aggregation and the means of bringing it about will be discussed in Chapter 11 (page 123).

Analysis of Soil Particle Size

A primitive method for separating the solid soil particles according to size, in order to assay the soil texture, consists in first sifting out the largest particles and then making a suspension of the soil in water. This suspension is allowed to settle, during which process the largest and heaviest particles sink first, while the others arrange themselves above them in layers according to size.

This rather crude and inaccurate procedure forms the basis of the much more exact "Bouyoucos hydrometer method," which is widely employed in American soil laboratories. The apparatus consists of a cylinder of standardized size which holds the soil suspension and, floating in the latter, a hydrometer, a calibrated glass tube closed at both ends. A small weight in the bulbous bottom end keeps the hydrometer upright.

The principles involved are the following:

(1) The denser the suspension the higher the hydrometer floats. As the particles settle out and the density decreases, the hydrometer sinks lower in the liquid. The calibration on the hydrometer tube permits the reading of grams of material per liter of water in suspension. This reading, divided by the weight of the soil and multiplied by 100, gives the per cent of the material in suspension.

(2) Since soil particles tend to cling together, they must first be separated and thoroughly dispersed. For this purpose 5 ml of normal sodium hexametaphosphate are added to 50 g of soil (or 100 g of sand). Distilled water then is added, and the material is deflocculated by stirring in a dispersing machine. The time of stirring required depends upon the type of soil (6 to 25 min).

(3) Since large particles have less surface in proportion to their weight, they settle down first. Therefore, sand settles first, silt second, and clay last. After 40 sec, according to the American system, and 4 min, according to the international system, sand is considered as having settled and the first reading on the hydrometer is taken. After 2 hr, when the second reading is taken, only clay is in suspension.

(4) Since temperature influences the density of water (see Chapter 7) and therewith the height at which the hydrometer floats, a temperature correction must be applied to the reading for accurate results. For every 1° above 67°F, 0.2 is added to the hydrometer reading, and for every degree below 67°F, 0.2 is subtracted.

Many European soil laboratories employ for scientific mechanical analysis a so-called "soil elutriating apparatus" (from the Latin word *eluere*—to wash out). With this apparatus the different-sized soil particles are washed out by a stream of water of accurately controlled force which passes through the soil suspension from bottom to top, taking the soil particles with it and depositing them in an adjoining vessel. It is evident that the smallest and therefore lightest soil particles will require no more than a very low velocity of water to wash them out. Thus these are removed first at a definite speed of water flow. When soil ceases to pass over into the measuring vessel, the water velocity is increased one step to remove the next larger size of particle, etc. This method is based on the principle that a definite relation exists between the size of the particle and the force of water required to wash it out.

Terms Applied to Soil Particles According to Size

Such a mechanical analysis determines the percentages of particles within a certain size range in a soil. The various grades in size are distinguished by generally accepted terms and are listed by the United States Department of Agriculture, starting with the largest, as in Table 5.1.

TABLE 5.1. SOIL PARTICLES CLASSIFIED BY SIZE

Names of soil particles	Diameter, millimeters
Fine gravel or 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
Clay	Less than 0.002

The International Society of Soil Science has revised and simplified this classification of soil particles (based on the work of A. Atterberg, 1912) as follows:

Separate	Diameter limits, millimeters
Coarse sand	2.00–0.20
Fine sand	0.20–0.02
Silt	0.02–0.002
Clay	Below 0.002

Loam Soils. Certain world-famous fertile soils, such as the soil of the Nile valley, are sedimentary in origin and consist of very thorough mixtures of sand, silt, and clay. It is this favorable mixture, quite as much as the yearly renewed deposit, which renders these soils so productive. Such sand-silt-clay mixtures, whatever their origin, are called loam soils, and among them the following soil classes are distinguished, according to the proportion of the various sizes of particles they contain: (1) gravelly sandy loam, (2) coarse sandy loam, (3) medium sandy loam, (4) fine sandy loam, (5) very fine sandy loam, (6) silt loam, (7) silty clay loam, (8) clay loam, and (9) stony clay loam.

Most agricultural soils will be found in this group, though other coarser or finer soil classes are not uncommon. The designations "sand," "silt," and "clay," refer only to the size of the particles, not to chemical composition. Even sand need not be silica. Especially when it originates from granite, it is likely to include solid particles of many other minerals.

Inorganic Colloids

The small particles of silt and clay likewise are extremely variable in mineral origin and in chemical composition. This fact must be borne in mind during all future discussions, which, otherwise, will not be understandable. Because of this difference in chemical composition the designation "inorganic colloids" (instead of clay) will be used in the following, although, according to size of particle, the material under discussion is clay.

Interest is focused on inorganic colloids (clay) because of the many vitally important reactions for which they are responsible and which are due mainly to the extremely small size of the particles concerned. Table 5.1 states only, diameter less than 0.002 mm, and no indication is given of the lower limit in the size of the particles.

Size of Clay Particles or Mineral Colloids. Actually, this lower limit is very difficult to establish. Formerly, it was believed that clay particles were more or less spherical in outline. Examination under the ultra- or electron microscope has definitely established, however, that they are infinitely thin plates or flakes which vary widely in outline and size. This makes it almost impossible to give diameter sizes. In order to convey at least an idea of the minuteness of these particles, it may be stated here that, considering only the largest diameter of each flake, their average size has been computed as approximately 0.0005 mm (or about 1/50,000 in.).

Because of the peculiar physical properties shown by particles of such minute size, they are classed in a separate branch of chemistry, called *colloid chemistry*. Soil particles of this nature are called *soil colloids*.

The properties of the soil colloids render them of vital importance in the dynamic soil processes (Part III) as well as in soil examination and soil conservation or improvement (Part VII).

6. THE PROPERTIES OF MINERAL SOIL COLLOIDS

The general designation "soil colloids" includes both organic and inorganic (or mineral) colloids. This is important to remember, since in any fertile soil both are present and both fulfill vital functions. The organic colloids have been discussed already on page 29. They are characterized by their amorphous, gluelike nature from which the name "colloid"—gluelike—has been derived.

NATURE OF MINERAL COLLOIDS

It is now quite definitely established that inorganic colloids are crystalline, having well-defined surfaces and resembling minute particles of mica. The apparent swelling, or increase in size, of these crystalline particles in the presence of water represents a natural phenomenon which is still under dispute. Some inorganic colloids[1] are able to hold considerable quantities of water, with apparent swelling, to many times their original size. Whether this water is only held adsorbed on the surfaces of the crystal or actually enters the crystal, being imbibed, is still a disputed point. Apparently, it varies with different colloids and may be influenced by conditions. The importance, for plants, of water thus held in reserve by the soil colloids has been stressed in the discussion of humus.

Plasticity of Mineral Colloids

The type of cohesion peculiar to the platelike inorganic colloids—which may be compared with the sticking together of two wet panes of

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[1] The fact that many solid substances—even some metals—can be artificially changed into colloids is significant. Such artificial colloids differ from the basic materials only in their properties—not in their composition. For this reason it has been proposed to use the expression "colloidal system" rather than to speak of "colloidal substances," but this designation has not found its way into general usage.

glass when they are slid over each other—gives clay one of its characteristic properties called *plasticity,* the ability to be molded. Use is made of this property in the molding of chinaware and earthenware, but it must be considered also in practical agriculture. Every farmer knows that heavy clay soil must not be plowed when wet, since it is likely to "puddle," i.e., to be pressed into lumps which later bake to stony hardness. (See also page 122.)

BASE AND ACID EXCHANGE

The most important and most intriguing property of the soil colloids (as pointed out on page 30) is their ability to assist in base and acid exchange. Because of the vital significance of the actions and reactions involved in this very complex process, it is now necessary to elaborate on the superficial description given previously.

The Arrhenius Theory (Electrolytic Dissociation)

The fundamental theory, which is used here to explain the processes involved, is the Arrhenius theory (or electrolytic dissociation theory), named after the man who first proposed it in 1887. This theory was developed from observations concerning what happens when an electric current is introduced into a solution of an acid, base, or salt which can conduct electricity. The dissolved compounds then appear to split into their component elements or into part-compounds, some of which wander to the positive and some to the negative electric pole, where their presence can be proved.

Arrhenius argued that the electric current did not cause the splitting (or dissociation), but that the dissolved compounds, by the very act of solution, were decomposed into part-molecules which were electrically charged, some positive and some negative. The electric current then served only to give them direction and caused them to wander to the electric poles opposite to their own charge.[2]

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[2] This principle is employed in electroplating objects which are to be covered with a thin, even coating of copper, nickel, chromium, silver, gold, etc. The object to be plated is submersed in a solution of a salt of the metal which is to be deposited and is connected to the negative electric pole. The positive pole must consist of a plate of the metal which is to be deposited: viz., in copper plating, a copper plate; in silver plating, a silver plate, etc. The introduction of a continuous electric current then causes the metal from the salt solution to be deposited very evenly on the subject which is to be plated. The Arrhenius theory explains this process, which was long misunderstood, very satisfactorily.

This theory is of interest for soil studies because, if one assumes, with Arrhenius, that a compound is decomposed by the act of solution, as soon as it is dissolved into variously charged particles or "ions," many soil processes can be explained. (See page 30 for an explanation of ion.)

The designation of this process as "electrolytic dissociation" is confusing, since no electric current is required for the dissociation, and there is no electric current in the soil. This expression, however, is used generally and, therefore, must be employed here also.

The Result of the Dissociation of Compounds. The contemplation of a few well-known dissociations will readily explain this matter. For instance, the simple inorganic salt potassium chloride has the chemical formula KCl. K stands for kalium (English: potassium) and Cl for chlorine. In a dilute aqueous solution this salt is not present any more as KCl but is dissociated into two parts, viz., K and Cl. It is possible to prove that K is charged electropositively, while Cl is charged electronegatively. The particles thus dissociated through the action of water are called *ions*. In the present case the electropositive kalium (or potassium) ions, with the chemical symbol K^+, and the electronegative chloride ions, with the chemical symbol Cl^-, are formed.

DIVALENT IONS. If, instead of potassium chloride (KCl), potassium sulfate (K_2SO_4) is dissolved in water, one obtains 2 K^+ ions for each SO_4^{--} ion. The ion of the sulfuric acid radical SO_4^{--} bears two minus signs, because it requires 2 K^+ ions for electrical equilibrium, and for this reason the SO_4^{--} ion is called *divalent*.

CATIONS AND ANIONS. The positively charged ions are called cations (because they are attracted by the negative electric pole—the cathode), and the negatively charged ions are called anions (because they are attracted by the positive electric pole—the anode). Cations are also called *bases*, and anions *acid radicals*.

Some of the most important ions generally contained in the soil solution are listed in Table 6.1.

Table 6 1

Cations		Anions	
Name	Chemical symbol	Name	Chemical symbol
Calcium ion	Ca^{++}	Chloride ion	Cl^-
Magnesium ion	Mg^{++}	Sulfate ion	SO_4^{--}
Potassium (kalium) ion	K^+	Carbonate ion	CO_3^{--}
Sodium (natrium) ion	Na^+	Phosphate ion	PO_4^{---}
Iron ion	Fe^{++} and Fe^{+++}	Nitrate ion	NO_3^-
Manganese ion	Mn^{++}	Nitrite ion	NO_2^-
Ammonia ion	NH_4^+	Hydroxyl ion	OH^-
Hydrogen ion	H^+		

Factors Governing Degree of Dissociation. How far a compound will separate into ions when it is dissolved in water (its degree of electrolytic dissociation in aqueous solution) depends upon the nature of the compound, the temperature, and, most of all, on the concentration of the solution. The concentration of a solution is expressed as percentage (parts per hundred) or in parts per million (ppm) and refers to the amount (in weight) of a substance which has been dissolved in a given volume of water. The more dilute (the less concentrated) the solution, the higher the degree of dissociation. Therefore, it can be assumed that, in the highly dilute soil solution, most inorganic compounds are, under average conditions, completely dissociated into ions.

A very singular position, among all the ions which occur in nature, is occupied by the electropositive hydrogen ion (the cation H^+) and the electronegative hydroxyl ion (the anion OH^-). When the two combine ($H^+ + OH^-$), they form the compound H_2O, which is water. The properties and significance of water are discussed later (Chapter 7). At present, only the properties of the ions themselves are being considered.

The Formation of Acids, Bases, and Salts. If the hydrogen ion, the cation H^+, combines with various other anions (not with the anion OH^-) it forms acids, such as hydrochloric acid (HCl), carbonic acid (H_2CO_3), sulfuric acid (H_2SO_4), and phosphoric acid (H_3PO_4).

The hydroxyl ion on the other hand, the anion OH^-, combines with various other cations to form "bases" (also called alkalies), such as potassium hydroxide (KOH), sodium hydroxide ($NaOH$), calcium hydroxide (or hydrated lime) [$Ca(OH)_2$], and ferric hydroxide [$Fe(OH)_3$]. All other compounds which result from the combination of all other cations and anions (without either H^+ or OH^-) are called salts, such as sodium chloride ($NaCl$), potassium sulfate (K_2SO_4), calcium sulfate ($CaSO_4$), and potassium phosphate (K_3PO_4).

Ions Resulting from Dissociation of Five Commonly Used Fertilizer Salts. As an illustration of the various ions which may be present in a given soil, it may be assumed that through liberal irrigation the following salts have gone into solution: calcium sulfate ($CaSO_4$), calcium phosphate [$Ca_3(PO_4)_2$], potassium chloride (KCl), sodium nitrate ($NaNO_3$), and calcium nitrate [$Ca(NO_3)_2$]. The soil liquid will then contain the following free ions: Ca^{++}, K^+, Na^+ as cations; and SO_4^{--}, PO_4^{---}, Cl^-, NO_3^- as anions; it is irrelevant to which salt these ions belonged originally.

Example of Base Exchange

With the principles of electrolytic dissociation through solution in water (the ion theory) thus made clear, it is now possible to proceed to a consideration of the exchange of cations and anions—the so-called base and acid exchange—which takes place between the soil colloids and the soil solution.

Consider a definite amount of soil (determined by weight), which, through extraction and analysis, is known to contain the cations Ca^{++}, Mg^{++}, NH_4^+, and Fe^{++} but no potassium (K^+). This soil is divided into two equal parts. To one part a carefully measured amount of potassium sulfate (K_2SO_4) is added. Subsequent extraction of both soils (the potassium-free and the potassium-containing soil) with an equal amount of water and comparison of the analysis of the extracts will produce the following results. The extract of the soil to which potassium sulfate was added will show considerably less potassium than the measured amount which was added. The extract of the potassium-free soil will show that the soil, to which potassium was added, now contains a great deal more free calcium than it did before. The explanation is that the soil colloids have adsorbed a large part of the potassium ions and have, in their stead, freed calcium ions which now are present in the soil solution.

The peculiar ability of colloids to cause or to facilitate base exchange has been exploited also for technical purposes and has been studied in detail in connection with installations which serve to soften so-called hard water.

NATURAL AND ARTIFICIAL MINERAL COLLOIDS, OR ZEOLITES

Mineral colloids (also called zeolites) sometimes occur locally in nature in fairly pure form, such as the greensand of New Jersey, called *glauconite* or the *bentonite* of Wyoming. Other names are given to other types of zeolites, depending upon their mineral origin. Zeolites have also been produced artificially (such as "permutit"), and by means of these artificial zeolites it has been possible to study the exchange process much more thoroughly than could be done with the natural soil colloids. The exchange which takes place can be demonstrated by means of the following equation in which the symbol Ze stands for zeolite:

$$\underset{\substack{\textit{calcium}\\ \textit{zeolite}}}{CaZe} + \underset{\substack{\textit{ammonium}\\ \textit{sulfate}}}{(NH_4)_2SO_4} = \underset{\substack{\textit{ammonium}\\ \textit{zeolite}}}{(NH_4)_2Ze} + \underset{\substack{\textit{calcium}\\ \textit{sulfate}}}{CaSO_4}$$

The exchange of the cations (calcium and ammonium) is very clear in this equation. In the soil such an exchange proceeds in very much the same fashion, but it must be pictured as considerably more complex, since a great many different cations are likely to partake simultaneously in the reaction.

What complicates matters still further is that not all soil colloids behave alike. Many are able to exchange bases (cations), as has been shown. It has been found, however, that some of them, at least, exchange anions with equal facility. It appears that some of the colloids can exchange both cations and anions, others can exchange only either one or the other, and still others appear to be completely inactive and exchange neither.

Exchange of Anions

The exchange of anions proceeds in very much the same manner as was explained for cations, and can be shown by means of equations which include the use of artificial zeolites (symbol Ze) in place of the soil colloids:

$$\underset{\substack{\textit{chloride}\\ \textit{zeolite}}}{ZeCl_2} + \underset{\substack{\textit{ammonium}\\ \textit{sulfate}}}{(NH_4)_2SO_4} = \underset{\substack{\textit{sulfate}\\ \textit{zeolite}}}{ZeSO_4} + \underset{\substack{\textit{ammonium}\\ \textit{chloride}}}{2NH_4Cl}$$

$$\underset{\substack{\textit{chloride}\\ \textit{zeolite}}}{3ZeCl_2} + \underset{\substack{\textit{potassium}\\ \textit{phosphate}}}{2K_3PO_4} = \underset{\substack{\textit{phosphate}\\ \textit{zeolite}}}{Ze_3(PO_4)_2} + \underset{\substack{\textit{potassium}\\ \textit{chloride}}}{6KCl}$$

$$\underset{\substack{\textit{sulfate}\\ \textit{zeolite}}}{ZeSO_4} + \underset{\substack{\textit{sodium}\\ \textit{nitrate}\\ \textit{(saltpeter)}}}{2NaNO_3} = \underset{\substack{\textit{nitrate}\\ \textit{zeolite}}}{Ze(NO_3)_2} + \underset{\substack{\textit{sodium}\\ \textit{sulfate}}}{Na_2SO_4}$$

COLLOIDS CARRYING ELECTRICAL CHARGES

In the footnote on page 71 were explained the principles of electroplating, in which an electric current causes the free ions contained in a solution to wander to the electric poles. If in the same manner an electric current is introduced into a suspension of inorganic colloids, the same type of separation occurs, and some of the colloidal particles will wander to the positive and some to the negative electric pole. In other words, they act like ions and reveal therewith that the colloidal particles themselves carry an electric charge, some negative and some positive. This reaction is utilized in the production of a particularly pure type of clay—called *kaolin*—which is used in ceramics. Its significance in the soil is explained in Chapter 11.

The complexity of the exchange processes which go on in the soil continually is now evident. The variously electrically charged colloid particles can be imagined as being surrounded by a swarm of loosely held (adsorbed) ions which react with each other in compensating their own electric charges. In their striving for electrical equilibrium they will change places with each other. Some will be freed or detached from the colloids and will enter the soil solution.

ABSORPTION OF IONS BY PLANTS

Ions which are free in the soil solution are immediately available for plant nutrition, but there is considerable evidence that plant roots are by no means entirely dependent on outside influences to make nutrients available for them. Carefully controlled experiments have shown that plants are able to extract nutrients from soil in amounts definitely exceeding those present in the soil solution. This can be explained only if one accepts the theory that growing plant roots, through close contact with the soil colloids, enter directly into the base exchange. It is a well-established fact that during respiration (absorption of oxygen and giving off of carbon dioxide, in other words, breathing of the roots), carbonic acid is formed. The hydrogen cation (H^+) of the carbonic acid is considered as exchangeable, and it is plausible to assume that it will serve to replace other cations held by the soil colloids if the contact between root and colloid is close enough. Actually, it has been possible to establish[3] that growing roots—especially in the root tip region—carry exchangeable cations (not only H^+) on their outer surface, and that the cation exchange between root surface and soil, which takes place readily, does not depend alone on root respiration or on other metabolic processes within the plants. Still other influences (enzymes and catalysts) which are at work will be discussed presently.

BASE-EXCHANGE CAPACITY

The maximal amount of cations which any soil can hold in exchangeable form (adsorbed by its colloids) is its base-exchange capacity. The latter can be established by leaching the soil *thoroughly* with a standardized solution of a neutral salt (such as ammonium acetate or barium acetate). This results in a complete exchange of all other cations which were held adsorbed by the colloids for the cations of the salt used in leaching. Through analysis of the extracting solution after it has gone through the soil sample, it is possible to determine the amount of cations which have been lost from it through colloid adsorption and therewith the total amount of cations held adsorbed by the colloids before leaching.

Base-exchange capacity is customarily expressed in milliequivalents

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[3] Williams, D. E., and Coleman, N. T., Plant and Soil, I, pp. 243–256 (1950).

per 100 g of soil (me/100 g) and varies widely in different soils, depending upon the amount and the kind of colloids present. It ranges from a few me/100 g to as much as 200 me/100 g, the highest values being found in organic soils. Inorganic soils (mineral soils) rarely have a base-exchange capacity of more than 75 me/100 g and usually have less than 50 me/100 g.

Base Saturation

The degree of base saturation, i.e., how close to full capacity are the colloids with such cations as Ca, Mg, NH_4, or K, depends upon the amount of H^+ ions present. When no H^+ ions are held adsorbed by the colloids and all the space available on them is occupied by other cations, the soil is base saturated. This can happen only at a relatively high pH level. (See page 106.) The more H^+ ions are present on the colloids, the fewer other cations can be held adsorbed, and the lower, incidentally, is the pH value. Such a soil is base unsaturated.

For instance, when the base-exchange capacity of a soil is 50 me/100 g, while the sum total of all the exchangeable bases present (except H^+) is found to be only 20 me/100 g, the degree of saturation can be expressed in percentages as follows: $(20 \times 100):50 = 40$. Such a soil, therefore, has a base saturation of 40 per cent. The other 60 per cent are H^+ ions.

High base-exchange capacity in itself is a desirable condition, because it denotes that the soil is rich in the right type of colloids which are able to adsorb and to exchange cations required as nutrients. Such a soil, therefore, will display a greater stability as far as its fertility is concerned than a soil with a low base-exchange capacity, because the adsorbed cations are less exposed to loss through leaching with water. Base-exchange capacity, however, expresses only the capability of the soil and supplies no information on the type of cations which actually are being held adsorbed. A soil of relatively high base-exchange capacity may, for instance, be saturated with sodium, calcium, or magnesium, or with several of these three, without any (or hardly any) of the other cations which are of much greater importance for plant nutrition. This would constitute a very unfavorable condition for plant growth.

CATALYSTS AND ENZYMES

Closely related to the base-exchange processes just discussed are certain substances present in the soil which are called catalysts and enzymes. In practice both substances may be lumped together, since their actions are very similar, and may be distinguished simply as inorganic catalysts and organic catalysts (enzymes).

Catalysts

Definition and Action of Catalysts. According to Oswald, catalysis may be defined as "the acceleration of chemical reactions through the presence of substances (catalysts) which do not appear in the end product of the reaction," which means that the catalysts themselves remain unchanged. This may be explained by the following example:

Hydrogen peroxide (H_2O_2)—used frequently as a houschold disinfectant—is a substance which decomposes, though very slowly, into oxygen and water. If certain materials (such as glass powder or metal powder) are added to the hydrogen peroxide, the decomposition of the latter is speeded up very considerably, though the material which was added (the catalyst) remains entirely as it was before. It does not enter in the reaction and "does not appear in the end product."

Measuring Catalytic Activity of Soil. The use of hydrogen peroxide, by the way, offers a simple and convenient means of measuring the catalytic activity of a soil, since the amount of oxygen produced within a given time is all that need be considered. This actually is the procedure which is usually followed to carry out such measurements.

Catalysts Initiating Reactions. Evidence has accumulated which tends to prove that catalysts (including enzymes) not only influence the speed of reactions which are in progress but can actually initiate them. This is explained by the theory that catalysts act in a similar manner as the previously discussed colloids, by adsorbing on their surface interacting compounds, which thus are brought into such close contact with each other that reactions are initiated which would not otherwise occur, or that reactions are speeded up which otherwise would be slow. It is further assumed that the products of catalysis are released by the catalysts almost as quickly as they are formed.

Enzymes

Inorganic catalysts in the soil are represented by certain clay colloids as well as by certain commonly present minerals, but the organic catalysts, or enzymes, are actually of greater importance. These are formed in the bodies of animals as well as in plants, and their actions in the soil must be considered as highly significant, since they remain effective for a very long time, even after the organism which has produced them is dead. Various microorganisms likewise produce enzymes, and the decomposition of organic matter (such as enumerated on page 28) is caused largely by the enzymes and ferments which are contained in the bodies of these microorganisms or are excreted by them.

Importance of Enzymes. As far as the living animal body is concerned, the numerous enzymes, each of which acts as a specialized catalyst in some specific conversion process, must be considered as vital factors in making life possible. Their immense importance becomes clear beyond doubt when the process is considered by which sugars are oxidized to carbon dioxide and water. These end products are obtained when sugar is burned over an open flame at a high temperature. The enzymes, through catalytic action, accomplish the same results at body temperature (37°C) and in this manner make available the energy which is required for growth, work, and body maintenance. In a similar fashion, enzymes are involved in nearly every process which occurs in living organisms (plants as well as animals).

The actions of enzymes have been known and employed for thousands of years, as in the leavening of dough and the fermenting of alcoholic beverages by means of yeast, though the cause of the results obtained was not understood. Now a great number of various enzymes have been isolated from plants as well as from the bodies of animals, and some of them are being employed in quantity for various purposes. They are usually sold in the form of powder. The chemical composition of the enzymes, however, is still incompletely known, and, so far, none has been synthesized.

Enzymes Involved in Decomposition of Soil Organic Matter. Since knowledge of the enzymes is still so incomplete and since new ones—so far known or suspected only from their actions—are being continually discovered, no real classification of these substances can be attempted, but it may be worth while to enumerate at least a few of those which must be considered as active in the decomposition of soil organic matter.

(1) Enzymes which accelerate the decomposition of carbohydrates, such as cellulase, effecting the decomposition of cellulose; amylase (diastase), effecting the liquefaction of starch; saccharase (invertase) which splits cane sugar into glucose and fructose; zymase which transforms sugar into alcohol and carbonic acid.

(2) Enzymes which accelerate the decomposition of proteins, such as pepsin, contained in the juice of the stomach and the main active agent of digestion; tryptase which liquefies albumins. These enzymes are also called proteolytic ferments (ferments dissolving proteins).

(3) Enzymes which accelerate the decomposition of fats, oils, or waxes, such as lipase, which decomposes fats into glycerol and fatty acids.

(4) Enzymes which render oxygen more active or accelerate its

effects, such as various oxidases, which effect the transformation of ammonia into nitrite and nitrate; of flowers of sulfur into sulfate; of gaseous nitrogen of the air into nitrous or nitric oxide, etc.

(5) Enzymes which accelerate the elimination of oxygen which is part of a compound, such as reductases, which transform nitrate into elemental nitrogen.

(6) Enzymes which accelerate the decomposition of hydrogen peroxide into water and oxygen; catalases.

All of these enzymes (or ferments) are present in the bodies of soil organisms or are excreted by them (exoenzymes). This applies especially to the fungi and bacteria. Usually, several enzymes which complement each other in their effects occur together.

Sensitivity of Enzymes to Heat and to pH Values. A rather important characteristic of enzymes is their sensitivity to heat. Most enzymes contained in the soil solution lose their ability to accelerate reactions if exposed to temperatures above 50°C (122°F), and they are completely destroyed at temperatures between 60 and 70°C (140 and 158°F). In a dry state, for instance in the dry tissues of seeds, enzymes can endure temperatures of 100 or even 120°C (212 or 248°F). This effect is of particular significance in the sterilization of soils. By means of the hydrogen peroxide test, mentioned previously, it has been possible to prove that soil which had been sterilized at a temperature of 100°C had almost completely lost its catalytic properties. The death of the microorganisms, which had produced the enzymes, cannot be held responsible, since, as stated previously, the effectiveness of enzymes does not depend on life processes. The pH likewise influences enzyme activity, the optimum varying with different enzymes.

As far as the catalytic action of soil is concerned, it must be stated that so far, at least, it is not possible to draw from it definite conclusions concerning the intensity of biological soil processes; i.e., the degree of catalytic action of a soil cannot be used as a standard for measuring the degree of activity of the soil microorganisms.

7. THE LIQUID SOIL CONSTITUENTS (THE SOIL SOLUTION)

The liquid matter contained in the soil, the soil solution, consists mostly of water, and, since without water no plant life can exist, it is well worth while to consider in more detail this vital compound and its many unique properties.

COMPOSITION OF WATER

The ancients considered water an element, which they believed to be not subject to further decomposition. This concept prevailed until 1781, when Cavendish demonstrated experimentally that water resulted from the combustion of what he called "air" and hydrogen. The credit for the correct interpretation of Cavendish's experiment, however, belongs to the great French chemist Lavoisier, who 2 years later showed clearly that water was a compound consisting of the elements hydrogen and oxygen. Later careful experiments of Dulong, Berzelius, and, especially, Dumas established that 11.11 volume parts of hydrogen combined with 88.99 volume parts of oxygen gave 100 volume parts of water, which is a proportion of 2 to 16. Since the atomic weight of hydrogen is approximately 1 and that of oxygen is 16, while the molecular weight of water is 18, the well-known chemical formula H_2O for water results.

THE WATER CYCLE

Water, as everyone knows, occurs in three different physical states or phases, viz., vapor, water, and ice. What is not considered as frequently as it should be is the fact that of the approximately 197 million square miles of earth surface, 140 million square miles, or approximately 71.3 per cent, are covered with water. This great preponderance of water surface over land surface is of considerable significance, since it governs the earth's climate. The continuous cycle of water is common knowledge. Through evaporation from the vast water surfaces, huge amounts of water are taken up by the air in the form of vapor. The clouds of vapor precipitate, when cooled, as rain or snow, which as runoff re-enters the rivers, lakes and oceans, ready to commence the cycle all over again. Much of the water that penetrates the soil and is taken up by plants likewise is eventually returned to the air as vapor.

THE BEHAVIOR OF SOIL WATER

For a survey of what happens to the water which enters the soil, as well as of the amounts of such water which will be available to plants, it is necessary to establish four groups which must be considered separately.

Water of Crystallization and Water Included in Hydrates

Chemically bound water is present in the soil first of all as *water of crystallization.* In the process involved, molecules of water attach themselves to the molecules of various substances, such as many mineral salts. For instance, when the sulfuric salt of copper, copper sulfate ($CuSO_4$), is dissolved in water and the solution is evaporated, crystals result which contain 5 molecules of water for each molecule of copper sulfate, according to the formula $CuSO_4 \cdot 5H_2O$. The same occurs with gypsum, calcium sulfate ($CaSO_4$), which attaches to each of its molecules 2 molecules of water, according to the formula $CaSO_4 \cdot 2H_2O$. Such combinations with water of crystallization occur quite commonly in the soil when it becomes very dry, but this has no influence on the solubility of the affected compounds when the soil is moistened again. On the other hand, it must be understood that although water of crystallization can be removed by heating the crystals, plants cannot withdraw it, which means that when soil becomes dry this particular amount of water is removed from the water reserves of the soil.

Water, furthermore, enters into combinations with other substances to form new compounds which are called *hydrates* or *hydroxides.* (See page 158.) This water likewise is beyond the reach of plants.

Water Held Hygroscopically

Hygroscopically bound water is held adsorbed as a very thin film on the surface of the solid soil particles. The total amount of water held in this manner expresses the degree of hygroscopicity of a soil, which varies with different soil types, depending on their composition. Table 7.1 will serve to give an idea of the wide range over which hygroscopicity varies in different soils.

TABLE 7.1 THE HYGROSCOPICITY OF DIFFERENT TYPES OF SOIL*

Soil type	Degree of hygroscopicity
Pure quartz sand	0.1 ✓
Sandy soil	1.0
Clayey sandy soil	1.7
Sandy clay soil	2.6
Clay soil	3.1 ✓
Stiff clay soil	4.1
Pure clay	5.8 ✓
Mixed soil with peat	6.2
Bog soil with garden soil	8.7
Peat-bog soil	21.7 ✓

* According to Mitscherlich, E. A., "Bodenkunde," 6th ed., p. 66, Paul Parey, Berlin 1950.

That hygroscopically held water is not available for plants becomes evident when the total minimum amount of water is established which a soil must contain in order to sustain plant life. Such an investigation readily reveals that plants commence to show disturbance of their growth when only two to three times as much water is present as corresponds to the hygroscopicity of the respective soil type.[1] Plants die when the soil contains only hygroscopically bound water.

Water Held in the Soil by Capillarity

Capillary water, mentioned previously (page 65), because of its paramount importance, requires further explanation. When rain falls it enters the surface soil layers through the pull of gravity, then is imbibed by the soil colloids and, as the water films spread and merge, is pulled farther downward by the exertion of downward-directed capillarity as well as by gravity. As the moisture moves downward, the water films are stretched thinner and thinner, until they reach their limit and are held suspended. The depth to which a certain amount of rain or irrigation water will penetrate in this manner depends upon the texture and the

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[1] When a completely dry soil is wetted with water, heat is released which is termed *heat of wetting* and which can be measured with a calorimeter. This heat of wetting quite naturally diminishes as more water is absorbed by the soil, and it becomes zero when all soil particles are completely moistened. Since the amount of heat developed is always in direct proportion to the degree of hygroscopicity of a soil it is possible to calculate mathematically the degree of hygroscopicity from the amount of heat measured, when a certain type of soil is wetted after having been completely dry.

structure of the soil. This means that the same amount of water that will wet a clay soil to no more than a few inches may penetrate in a sandy soil to as much as 2 ft. In either case, however, the boundary line between the moist upper soil and the still dry lower soil is drawn rather sharply and evenly.[2]

Field Capacity. The amount of water which a soil can hold by capillarity—after the gravitational water, moving downward in the larger spaces, has drained away—is its field capacity. This ranges from about 5 per cent in very sandy soil to about 35 per cent in clay loams, and it may take from a few hours to 2 or 3 days after a rain or irrigation for a soil to reach its field capacity.

When additional water is applied or more rain falls on a soil which has been moistened to the depth of a few inches, the already moist upper layer does not become wetter, but the water penetrates deeper. How much deeper depends not only upon the amount of water supplied but also upon the amount of water required to satisfy field capacity.

PRACTICAL APPLICATION OF PRINCIPLES OF FIELD CAPACITY. To understand this process is important for a gardener. Because of the peculiar way in which water moves in the soil, a light surface sprinkling will achieve nothing. It may moisten the soil to a depth of ½ to 1 in., but below that the soil will remain as dry as it was before. The reason for the old advice to water less frequently—not to sprinkle a little bit every day but to soak the soil at each watering to a depth of at least 6 to 8 in.—can now be understood.

FACTORS INFLUENCING HEIGHT TO WHICH WATER MAY RISE BY CAPILLARITY. The height to which water may rise by capillarity is limited not only by the texture and structure of the soil (governing the size of the pore spaces, see page 65) but also by the resistance resulting from inner friction. This resistance decreases with rising temperature. If the resistance at 0°C is taken as 100, the resistance at 25°C is only 49.9, which means that the water is enabled to rise correspondingly higher at a higher temperature. The commonly occurring dropping of the water table during summer is thus at least partly compensated for.

Water Movement Under the Influence of Gravity

Gravitational water represents the surplus beyond the field capacity of the soil which drains away to the water table or which runs off on the

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[2] The tenacity with which water is held in a given soil through the force of capillarity may be determined by means of a simple apparatus, called a *tensiometer.* [Richards, L. A., and Gardner, W., *J. Am. Soc. Agron.,* 28, 352 (1936)] Several other similar methods have been developed by others.

surface. The latter likewise follows the pull of gravity in seeking lower levels without penetrating into the soil. This is why gravitational water is of next to no importance for plant growth, though it does influence the water table and, in fact, serves to maintain it. On the other hand, it is the gravitational water which causes erosion and, therewith, the loss of precious topsoil as well as of plant nutrients if nothing is done to prevent it from running away on the surface.

THE WATER TABLE

In all regions of the earth with a reasonable amount of annual rainfall a hole dug in the ground at almost any place will eventually encounter a completely saturated soil layer. Water then will rise in the hole to the limit of the saturated soil, where it remains at a definite level. This level is called the water table, and such subsoil water may be either stationary or moving. In the latter case one speaks of a subsoil stream of water, which gives origin to springs when coming to the surface at lower topographical levels, or which may be tapped by means of artesian wells.

Height of the Water Table

The height of the water table varies considerably from place to place, depending largely upon the topographical location. It is evident that in a river valley the water table can be expected to be relatively near the surface and far below the surface of a hilltop. The water table varies also with the season. A false water table sometimes develops above the true one when impermeable soil layers or bowl-shaped depressions in underlying rock prevent the water from joining the true water table.

Influence of the Water Table on Plant Growth

Under certain conditions—permitting water movement and therewith aeration—a fairly high water table (4 to 5 ft below the surface) may be very favorable, but this is an exception. A water table 20 to 25 ft below the surface—approximately 3 ft below the root zone, depending upon the types of plants cultivated—is more likely to be generally advantageous. Water may rise from the water table by capillarity, but in the average loam soil it rarely rises more than 8 ft. Besides, the capillary movement through several inches is much more effective and, therefore, more important than the movement through several feet. Since the roots of comparatively few plants penetrate deeper than 25 ft into the soil, a water table much below 25 ft is negligible in its influence on plant growth. With a water table below 30 ft—which occurs very frequently—plants must depend entirely upon the water which reaches them from above and which is held in the soil by capillarity.

Damage Resulting from Lowering the Water Table

Careless lowering of the water table—through wells or pumps or through ill-considered drainage—from a level at which it did assist the vegetation to one where it cannot do so any more—must, by necessity, engender very serious consequences.

As an example of what may happen when the water table is lowered may be mentioned the region of the upper Rhine River, with France (Alsace) on one side of the river, and Germany (Baden) on the other. Less than 100 years ago this was one of the most fertile regions of Europe. Straightening of the river and deepening of its bed, to prevent recurrent floods, resulted in lowering the soil water table of the adjacent area by 15 to 30 ft. The building of a concrete-lined canal, for the purpose of facilitating barge traffic as well as of gaining hydroelectric power, made matters still worse, since the now almost empty river bed acted as a huge drainage ditch. The result was that thousands of formerly rich farms were completely ruined and that the whole region is now changing to infertile steppe covered with thorn scrub. This situation can be remedied only through restoration of a higher water table by transforming the empty river bed into a series of slowly overflowing lakes and by diverting part of the canal water into an irrigation system. The huge expense and the conflicting interests involved have, so far, prevented any such scheme from being seriously considered. Similar bungling attempts to improve upon nature have, by upsetting nature's balance, ruined vast stretches of land in many other countries.

DENSITY AND WEIGHT OF WATER

The many unique properties of water include the peculiarity that water has its greatest specific weight at 4°C (39.2°F) which means that the same volume of water weighs less at all other temperatures. This fact was used to establish the unit of the metric weight system, according to which the weight of 1 cubic decimeter (cu dm) (1 cu dm = 1 liter, or 1.057 United States liquid quarts) of water at a temperature of 4°C and under the standard atmospheric pressure of 760 mm was established as 1 kg (approximately 2.2 lb). According to the United States or British weight system, 27.692 cu in. of water at 4°C and under 760 mm atmospheric pressure are the equivalent of 1 lb (avoirdupois).

Consequences of the Changing Weight and Density of Water

This strange behavior of water is significant for the understanding of many natural processes. If water at all temperatures above or below 4°C weighs less, this means that more than 1 cu dm of water at higher or lower temperature has to be taken in order to obtain the weight of 1 kg, or, in other words, the volume of water increases at temperatures above or below 4°C (39.2°F). Therefore, if a sheet of water (a lake for instance)—with a temperature of say 50 or 60°F—is cooled, the water contracts at first, and the heavier cooler water sinks to the bottom, while the lighter warmer water rises to the top. This continues until the whole mass of water is cooled to a temperature of 39.2°F, when the reverse happens and the surface water expands with further cooling, therewith becoming lighter, and now floats on the warmer water beneath it. Therefore, no more mixing occurs, and the warmer water does not rise to the top any more. In consequence, a lake rarely freezes suddenly all the way through to the bottom, and, during light frosts, a shallow puddle may freeze, while deeper bodies of water do not even develop a crust of ice on the surface.

Why Ice Floats Partly Above the Water. The rather sudden expansion, by approximately 10 per cent of its volume, when water turns to ice at 32°F is the reason why ice floats partly above the water. It is common knowledge that the largest part of a floating iceberg ($9/10$ of its volume) is below the water and only $1/10$ is above it. This is why icebergs constitute such a serious danger to shipping. On the other hand, if ice were not greater in volume and therefore not lighter than water, an iceberg would not appear above the surface at all and would be still more dangerous.

Effects of Pressure Resulting When Water Expands. The pressure which develops when water contained in the cracks and fissures of rocks turns to ice and expands is considerable and is capable of cracking the hardest rocks. The repeated alternate freezing and thawing of water, as occurs especially during fall and spring, is one of the main forces in breaking up and finally even pulverizing the primary rock.

An enormous pressure likewise develops when the spring sun warms water, contained in fissures or in the upper soil layers, to a temperature above the critical point of 39.2°F, while lower or surrounding parts remain frozen. The sudden appearance of holes and cracks in roads and paved streets, and the collapse of retaining walls—common occurrences during the first sunny spring days—are demonstrations of this fact.

ELECTROLYTIC DISSOCIATION OF WATER

Another interesting and important property of water is its electrolytic dissociation. It has been pointed out previously (page 71) that salts in aqueous solutions are dissociated in varying degrees into cations and anions, acids into hydrogen ions and anions, and bases into cations and hydroxyl ions. Water itself also is partially dissociated into hydrogen and hydroxyl ions, according to the equation $H_2O = H^+ + OH^-$. The degree of dissociation is an important factor, as will become apparent when the reaction (the pH) of the soil is discussed. (See page 106.)

Degree of Dissociation of the Ions of Absolutely Pure Water

To determine the degree of dissociation of absolutely pure water, it was necessary first of all to produce water of the greatest possible purity, since the presence of even the very smallest amounts of dissolved substances would make any such measurements inaccurate. Many-times-repeated distillation (in the presence of certain substances) in platinum apparatus has succeeded in producing such water. Through various ingenious methods it is then possible to measure very accurately the respective amounts of H^+ and OH^- ions which are contained free in a given amount of water, and it was found that 1 g hydrogen ions (H^+) and 17 g hydroxyl ions are contained in 10 million liters of absolutely pure water.

The atomic weight of hydrogen is 1, and that of oxygen is 16. The hydroxyl ion (OH^-), therefore, has the equivalent weight of $1 + 16 = 17$. From this it is evident that OH^- is 17 times as heavy as H^+. Since the weight proportion of H^+ to OH^- in the dissociated part of the water is 1 to 17, it must be assumed that the 1 g of H^+ is made up of just as many ions as the 17 g of the 17 times heavier OH^-, in other words that the amounts of H^+ and OH^- ions present must be equal.

The condition in which these two ions are present in equal amounts is called neutral. In measuring conditions above or below neutral, when either the hydroxyl or the hydrogen ions predominate, it is the generally accepted practice to consider only the amount in grams of the hydrogen ions which are present in a liter, and this amount is expressed in a number as the *hydrogen-ion concentration.*

Origin of pH 7

As was pointed out above, 10 million liters of absolutely pure water contain 1 g of free hydrogen ions. Therefore, the hydrogen-ion concentration of such water is 1 divided by 10,000,000 or 0.0000001. Since 1 divided 7 times by 10 gives the same result (the same quotient) as 1 divided by 10,000,000, the figure 0.0000001 can be written in simpler form as 10^{-7}. The high-placed figure 7 is designated as the logarithm of 10,000,000 (1 multiplied 7 times with 10 gives 10,000,000). $^{-7}$ is the logarithm of 0.0000001, the minus sign denoting that a division, not a multiplication, has taken place. The suggestion that the logarithms be used instead of the small figures—such as 0.0000001, which are very subject to error in writing and interpretation—was first made by the Danish biologist S. P. L. Sörensen.

He suggested, furthermore, leaving out the minus sign, using the positive logarithm instead, and employing in place of the long term "hydrogen-ion concentration" the symbol pH. The capital letter H then stands for hydrogen-ion concentration, which is being expressed, while the small letter p, which was chosen at random, may be taken to signify that the values given are logarithmic ones. According to this generally accepted procedure, absolutely pure, and therefore neutral, water can be stated as having pH 7. It is still necessary to add, however, that pH values vary with changing temperature and that the value of pH 7 for pure water applies to a temperature of 22°C (71.6°F).

Naturally, all other liquids (in particular aqueous solutions), which contain equal amounts of H^+ and OH^-, likewise have a pH of 7. (See also Chapter 10, and Appendix I.)

WATER AS A SOLVENT

The ability of water to act as solvent for a great many salts, acids, and bases—many more than any other solvent—as well as the fact (see page 72) that most substances when dissolved in water are, through the very act of solution, more or less completely dissociated into ions, must likewise be included in this enumeration of the properties of water.

PURITY OF WATER

Absolutely pure water does not exist in nature. Even rain water contains various elements and compounds, such as oxygen, chloride, sulfate, nitrous oxide, and ammonia, which it has adsorbed from the air. Water which trickles through the soil—the soil solution—contains many water-soluble substances of organic as well as inorganic origin. These dissolved substances, in fact, constitute the plant nutrients.

ABSORPTION OF WATER AND NUTRIENTS BY PLANTS

The amounts of the various plant nutrients contained in the soil solution are subject to constant change under the influence of rain, drought, heat or cold, day or night, the absorption by plants, and the activities of microorganisms. The question: "What is the most favorable concentration of nutrients in the soil solution; which concentration is too low and which too high?" is frequently asked.

To answer this question in a general manner is impossible, since too many factors governing the optimum are involved. Not only do different plants have different requirements, but different nutrients become of prime importance at different periods of the growing season. Tolerance to high concentration of salts, as well as the ability to obtain nutrients directly from the soil colloids, also varies with different plants in different types of soil and at different seasons. The age of the plants and their state of vigor and health likewise must be considered.

A clear understanding of the highly complex phenomena involved in the absorption of water and nutrients by plants is very important, since an intelligent approach to the treatment of plants is quite impossible without it. Roots, the absorbing organs of plants, consist of cells separated by membranes. How and under what impulse do water and nutrients pass through these membranes and cells and on into the upper parts of the plant? To explain this, two processes—diffusion and osmosis—which are closely linked, are now discussed.

Diffusion

Diffusion concerns the spreading of a solution through a liquid which serves as its solvent. Since, in the case of soil, water and plant nutrients are concerned, the point of interest is the manner in which an aqueous solution of a nutrient salt behaves when it is added to more or less pure water. What happens is that the solution gradually penetrates, diffuses, throughout the water, entirely of its own accord and without stirring, until it is evenly mixed with the water and is proportionately diluted.

A simple demonstration of this process can be carried out as follows:

A concentrated solution of copper sulfate, which is blue in color and heavier than water, is put into a glass cylinder. Pure water then is carefully poured in on top, without disturbing the copper sulfate solution. Being lighter, the water will float on top, and at first there will be a fairly clear division between white and blue color. Gradually, the blue copper sulfate solution then rises against gravity and commences to spread through the water, until eventually a perfectly uniform mixture results and the liquid throughout the cylinder has the same color, now, however, a somewhat lighter blue than before.

Action of Diffusion in the Soil. This process is intimately involved when fertilizer salts are applied to the soil. Such salts are supposed to dissolve, which is the case if sufficient water is present, but it is not desirable for the solution which is formed to remain concentrated in one spot. It must spread (diffuse) throughout the adjacent soil in order to reach the plant roots. The above experiment with copper sulfate and water shows that it can be counted on to do this all by itself, though slowly. What happens if too much fertilizer is applied, or if it is applied too close to the plants so that concentrated solutions reach the roots, will be discussed presently.

Osmosis (Diffusion Through a Membrane)

Diffusion may proceed in the same manner through a permeable membrane, if such a membrane is interposed between an aqueous solution and water. Water will pass through (diffuse) into the solution, and the solution will diffuse into the water, until the degree of saturation is equal on both sides of the membrane.

Most biologically important membranes, such as the membranes of plant cells, are not permeable in this sense but, instead, show a different degree of permeability for different substances. For instance, they may be freely permeable to water and only partly so, or even impermeable, to various solutes. Such membranes are frequently called *semipermeable,* but the term *differentially permeable* is preferable and will be used henceforth in this text.

The classical experiment to demonstrate this process employs a pig's bladder, filled with a concentrated sugar solution, which is immersed in a container with water. The pig's bladder, being differentially permeable, permits free entry of the water into the bladder but only very slow diffusion of the sugar solution to the outside. The result is that the amount of liquid inside the bladder increases rapidly, setting up a pressure which becomes visible through the increasing distention of the bladder. This process, which can be defined as "diffusion through a differentially permeable membrane," is called osmosis (from *osmos*: impulse), and the pressure which results therefrom is called *osmotic pressure*.

In the case of the pig's bladder, the sugar solution also will very slowly diffuse out into the water and, if one waits long enough, the bladder will become flaccid again. Eventually, the strength of the solution will become the same outside and inside, though it will be proportionately more dilute than the original solution.

Pfeffer's Artificial Osmotic Cell. In order to measure the osmotic pressure which develops as the consequence of this type of diffusion, it is necessary to have a membrane which is rigid, so that it does not distend. In addition, it must be permeable only to water and impermeable to the solute. The first man to take such measurements was Pfeffer, who used for his now classical experiments a porous clay cylinder coated with copper ferrocyanide. The pressure which develops in such an artificial osmotic cell can be measured with a mercury manometer.

Action of Living Cell Membrane in Osmosis. The process of water and nutrient intake by plants is analogous to the one outlined above but with the important difference that the living membrane of a root hair—the smallest and most active, unicellular branchlet of a growing root—cannot be expected to act in exactly the same manner as a pig's bladder or as Pfeffer's artificial osmotic cell. Such a living membrane, quite naturally, is differentially permeable in more than one sense. Not only does the degree of its permeability vary with different substances, but it changes also at different times under the influence of the metabolic processes going on inside the plant. This means that, under certain conditions, a substance may diffuse freely through a membrane, whereas at other times the membrane is almost impermeable to it.

These complex processes are still under study, but the fact is generally recognized that water and nutrients are taken in by plants quite independently of each other. This means that, depending on circumstances governing need, a plant is able to take in a great deal of water with very few solutes in it, in spite of their presence in the soil solution. Under another set of circumstances the same plant is able to take in certain salts with very little water, in spite of the fact that plenty of water may be available. If one considers that, under normal conditions, the concentration of salt solutions within the roots remains fairly constant and is always considerably higher than that of the surrounding soil solution, it becomes evident that this is not a simple diffusion of water into a concentrated solution nor a diffusion of solutes into a more dilute solution. These processes are still based on the principles of osmosis, but it is erroneous to believe that the functions of living organisms can be explained entirely by means of experiments with nonliving membranes.

Oxygen Required for Intake of Nutrients

That these phenomena are life processes becomes fully apparent when it is pointed out that plant roots are able to absorb nutrients from the soil only in the presence of oxygen. The reason is that oxygen is required for the respiration of the roots, and the energy which is released in respiration is essential for the movement of dissolved substances (solutes) across the cell membrane and into the cells—from a weak solution into a concentrated one (against the gradient).[3] The latter process might be compared with forcing water to flow uphill, against its natural inclination. Since this represents work, force or energy is required to accomplish it. (See page 145.) Lack of soil aeration, therefore, results in starving the plants because of interference with the intake of minerals by the roots. Very deep planting of trees, shrubs, or perennials, especially in a heavy clay soil, will produce the same effect.

Oxygen Required for Intake of Water

An overabundance of water, however, producing complete soil saturation, will also, for the same reasons, interfere with the intake of water itself, so that it will become difficult for plants to absorb as much water as they need, in spite of the fact that plenty is present. Certain potted plants—cinerarias for instance—actually show wilting when they are kept continuously soaking wet. Eventually, their roots die and rot.

That inundation, when prolonged for more than a very few days, will kill most plants is common knowledge. The reason is lack of oxygen, causing the metabolic disturbances just described.

All this applies only to normal dry-land plants. Bog plants or water plants have differently constructed roots with internal air passages which allow oxygen to pass down from the leaves..

Favorable Concentrations of Nutrients

What concentrations of nutrient salts are most favorable for plant growth? This can be answered rather accurately for water culture, so-

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[3] Under certain conditions water is absorbed by the plant roots in the form of vapor which automatically excludes the solutes. This process, though, also requires energy.

called "soilless" plant culture (page 169), under controlled greenhouse conditions, but for the soil solution and for plants growing in the open, no precise answer is possible because of the many factors involved. Nor would it do any good to know of a definite strength of solution, since there is no means of controlling it and of maintaining it in the open soil. The fact, however, remains that a dilute solution is more favorable to plant growth than a concentrated one. Translated into action, this means that several light applications of fertilizer are always preferable to one heavy application.

Effects of Soil Solution with Too High a Concentration of Salts

What happens when the concentration of nutrient salts in the soil solution becomes too high? When the previously described experiment with the pig's bladder is reversed and water is placed inside the bladder with a strong sugar solution surrounding it, the water will move out of the bladder very quickly and the bladder will shrink. This result is sometimes quoted as an explanation of what will happen to a plant under similar circumstances: "If the concentration of the soil solution becomes higher than the concentration inside of the plant, water will be drawn out of the plant and the plant will wilt and die."

This explanation, however, is so oversimplified that it is extremely misleading. A plant is a very complex body, consisting of innumerable cells. Each cell has several membranes and all of these, as well as the cell contents, will offer considerable resistance to the removal of water. The metabolic processes within the plant, such as photosynthesis and transpiration, require a continuous supply of water and will, therefore, exert a tremendous pull which opposes the very much weaker force of the outside salt solution.

Withdrawal of Water from Roots. Under extreme circumstances water will undoubtedly be withdrawn from the root hairs and root tips which, in consequence, will collapse and die. Though it is unlikely that water will be removed from the rest of the plant, this is serious enough and will result in the death of the plant. Actually, in a normal soil, under field conditions, and as long as only properly selected fertilizers are used and are broadcast, it is next to impossible to create concentrations high enough to result in the withdrawal of water from the plants. This can happen only if large amounts of sodium chloride (common salt) are applied, or if, through an accident, a large amount of fertilizer is spilled in one place and is not removed.

"Burning" from Overlarge Amounts of Fertilizer Salts. Damage, however, may result long before withdrawal of water occurs, and, since this happens rather frequently, it is actually of much greater interest. As the concentration of solutes in the soil solution increases, water becomes ever less and less freely available to the plant. To counteract this condition, the plant raises the concentration in its root system by taking in more solutes. This, however, results in decreased transpiration, depletion of available carbohydrates required for growth, stoppage of growth, curling of the youngest leaves, dropping of flowers, and sometimes temporary wilting. Tomatoes, which are rather shallow-rooted plants, are notorious for reacting in this fashion to a comparatively light overdose of fertilizer or to an application too close to their roots. If the concentration of salts in the soil solution rises so high that entry of water into the plant is completely stopped, this will also result in wilting and, if prolonged for more than a very short time, in the death of the plant, even if no actual withdrawal of water from the root hairs occurs.

Factors Influencing Plant Injury. As indicated previously, plants are not equally sensitive to an overconcentration of all substances. Furthermore, their tolerance to overconcentration of various salts in the soil solution varies under the influence of numerous factors, such as air temperature, light intensity, carbon dioxide content of the air and of the soil atmosphere, relative humidity, wind velocity, rainfall, kind and age of the plant, rate of growth, type of soil, and pH of the soil. Translated into action, this means that under one set of conditions a fairly heavy application of fertilizer may produce perfectly satisfactory results, while the same amount under a different combination of circumstances may cause serious damage. This is a rather frequent observation and emphasizes the previous admonition to apply fertilizer salts in several light doses rather than in one heavy one.

With potted plants, where soil and roots are confined in a limited space, the danger of overconcentration of salt solutions and, therefore, of injury, is much greater than in the open field. Even local injury to part of the roots through careless application of concentrated fertilizer may be fatal to a sickly plant with a poor root system. Potted plants, therefore, should always be given only dissolved fertilizer in very dilute form.

INFLUENCE OF WATER TEMPERATURE

This discussion of water cannot be closed without considering the influence which the temperature of the water has on the development of plants. The sensitivity of plants to cold water varies considerably. Plants native to northern regions are usually quite indifferent to it, but certain tropical or semitropical plants are rather easily injured when watered with cold or chilly water (40 to 50°F). Notorious in this respect is the African violet (*Saintpaulia*) which—though its stiff leaves do not wilt—simply does not thrive, and pines away slowly when watered continuously with water near 39°F. Other plants wilt rather rapidly and are slow to recover when they are watered with cold water, after having been kept in a warm greenhouse or warm room. The reason for this effect is believed to be reduced availability of water owing, in part, to the greater density and therewith the more sluggish movement of water at 39°F (see page 86) and, in part, to a decrease in permeability of the root membranes as well as increased viscosity of the protoplasm of the living root cells. Slowing down of the metabolic processes within the root cells and decrease of root growth further contribute to reducing the intake of water. In other words, the effect is not unlike that of lack of oxygen which was discussed on page 93. The general admonition to water house plants always with water of room temperature is well worth heeding.

8. THE GASEOUS SOIL CONSTITUENTS (THE SOIL ATMOSPHERE)

Purpose of Soil Aeration

Reference to the presence of various gases in the soil has been made previously in this text, and any farmer who drains his fields by means of open ditches, draintiles, or subsoil plowing actually practices aeration. The water which is drained away is replaced by air, and the beneficial results obtained are caused mainly by making oxygen more freely available to the roots and giving surplus carbon dioxide a chance to escape. The air is contained in the pore spaces of the soil in the same manner as the soil water, and a free exchange and flow of water and air is of extreme biological importance. The main reasons for the injury to plants which occurs when a soil becomes waterlogged have been explained in the preceding chapter. Certain toxic substances, such as ferrous iron, hydrogen sulfide, or nitrite, formed in the soil through reduction (page 161) when atmospheric oxygen is lacking, further aggravate this condition. Very similar is the effect which occurs when, during the artificial changing of topographical levels—for instance in terracing—soil is filled in around a tree to a height of several feet. In such operations it is necessary—in order to save the life of the tree—to provide, before the fill is made, a system of air passages radiating out from the trunk of the tree. Tile drains or rows of stone rubble, placed so as to resemble the spokes of a wheel with the tree trunk as axis, will answer this purpose.

Composition of the Soil Atmosphere

In order to understand the significance of the gaseous constituents of the soil, it is necessary to realize that the mixture of gases in the soil is not the same, in composition, as the air above the surface. One very important difference is that under average conditions the soil atmosphere has a humidity of close to 100 per cent, which means that it is never far from being saturated with water vapor. That such a high humidity is ideal for root growth as well as for the development of various fungi and bacteria needs no emphasis.

Significance of Carbon Dioxide in Soil Atmosphere. Another difference is that in a soil suitable for plant growth the carbon dioxide content of the soil atmosphere is much higher than—in extreme cases as high as 70 times—that of the outside air. It has been pointed out previously that an overaccumulation of carbon dioxide is inimical to root growth. This, however, can happen only when the soil atmosphere stagnates because its normal flow and movement is prevented by unfavorable conditions. Under conditions of proper drainage and aeration, which is favored by a good crumb structure (page 66), a high carbon dioxide content is extremely desirable and can, to a certain extent, even be used as an index of soil fertility. Many bacteria, in particular those which are active in the important transformation of ammonium into readily available nitrates, require carbon dioxide for their metabolic processes.

The importance of the carbon dioxide which escapes to the outside air and thus becomes available for photosynthesis must not be underestimated either, since this represents the main source of this gas for all higher plants. The important role played by carbonic acid in making various nutrients available to plants likewise enters this picture. (See page 158.) Carbon dioxide originates in the soil mainly through the decay of organic matter, specifically through the activity of the various soil microorganisms, the amounts produced by plant roots during respiration being rather insignificant in comparison. This fact once more emphasizes the vital influence of organic matter in all forms on the complex processes which are included in the term *soil fertility*.

Other Components of Soil Atmosphere and the Forces Governing Its Movement. The importance of oxygen as a component of the soil atmosphere has been stressed in the discussion of water, and little further comment is necessary. It may yet be mentioned, however, that under structurally favorable soil conditions, water itself will serve as a carrier of oxygen. Because oxygen is consumed in the processes accompanying decomposition of organic matter, its proportional content in the soil atmosphere is always considerably lower than in the open air. The nitrogen content of the soil atmosphere is approximately the same as that of air (80 per cent). Under conditions of poor aeration and poor drainage, other gases, such as methane (marsh gas) and hydrogen may accumulate in the soil atmosphere in considerable quantities.

The exchange of gases between soil and air is governed mainly by the movement of water, though changes in temperature or in barometric pressure likewise cause gases to move into or out of the soil. The latter process has sometimes poetically been called "breathing of the earth," though it compares more closely with artificial respiration, since the earth itself does not assist.

9. PHOTOSYNTHESIS

Up to this point a great deal has been said about the various gases and liquids which plants require for the building of their bodies as well as about the soil conditions which favor or influence plant growth. The why of all this, however, can hardly be understood if one does not have at least a notion of how the plant uses these materials. A short discussion is, therefore, included here of what is scientifically termed *photosynthesis,* undoubtedly the most important of all natural processes as far as life on earth is concerned.

Utilization of the Energy of Light

Green plants have the unique ability to utilize the energy of light in order to put together (to combine) various gases, liquids, and minerals from air and soil, so as to form the building blocks (the chemical compounds) of which the plant cells and, therewith, the whole structure of the plant's body, is composed. The means by which this is accomplished, one of the most coveted secrets of life, have long been the object of scientific research. It is evident that if man were able to manufacture sugar and starch directly from water and air (carbon dioxide), the world's hunger would be vanquished forever. Recently, the all-important basic steps of the process, as it takes place within the plant, have been revealed experimentally, and the ultimate effects of this immensely important discovery can be expected to be far reaching. It will undoubtedly be a long time yet, however, before large-scale manufacturing processes can be developed and can be brought to such perfection that they actually are able to take over at least part of the food production now resting solely upon agriculture. So far, plants and plants alone have made human and animal life on this planet possible, and, since much more than food is involved in the plants' services to man, this is the way it is likely to remain, regardless of the depth to which men penetrate into the secrets of nature.

Manufacture of Carbohydrates

Laboratory studies of photosynthesis established first of all that the gas carbon dioxide is taken up by the leaves of a plant from the air, while at the same time soil water enters the plant through the roots (page 93) and is moved up to the leaves. The water carries in solution various nutrient compounds originating in the soil. Some of these nutrients are indispensable even in the beginning of the processes here discussed, as will be explained presently. The basic process, however, is the mysterious welding together of the hydrogen ions of the water with the carbon dioxide of the air into so-called carbohydrates (page 28): first of all sugar, but later also starch and other still more complex compounds. In this process some of the oxygen of the water is freed and is released into the air.

Chlorophyll

This feat is performed by minute green bodies, called chloroplasts, which are visible in the living green plant cell only under a microscope. The green coloring matter is called *chlorophyll*. The chemical composition of chlorophyll is known, but so far nobody has been able to produce it synthetically so that it actually functions in the same manner as does the natural product.

Preservation of Energy

The energy making possible the process of "welding together" ions—which first have to be torn away from other compounds and mixtures—is the energy of light. In nature, sunlight supplies this energy, but artificial light will serve just as well. The energy thus used is not by any means lost, however, but is preserved according to the law of the preservation of energy which says that energy seemingly lost must always appear elsewhere. Man himself employs this preserved energy constantly, especially in the form of heat, light, and mechanical motion, whenever he uses wood, coal, oil, and other materials derived from plants.

The plant itself is able to conserve energy for future needs in the form of reserve starch which, particularly at the end of the growing season, is stored away in the trunks and branches of trees, or in tubers such as potatoes. In spring, when life renews itself, this energy is remobilized for use in the growth of the plant by reconverting the starch into sugar.

Oxygen in Energy Conversion

The astounding fact—one of the most profound marvels of nature—is that plants are able to convert the energy of light, the most evasive of all forces, into temporarily immobile but reconvertible chemical energy. The mainspring of this energy conversion is oxygen, which was torn away from the hydrogen ions of water during photosynthesis and was released into the air. In consequence, all carbohydrates and, in fact, all organic matters are combustible—which means that they have an attraction (affinity) for oxygen—and they release energy under combination with oxygen in proportion to the amount of carbon they contain. (See page 242.)

Importance of Air and Water

When attention is thus focused upon the importance of carbon dioxide and water in a plant's life, the impression is created that soil-derived mineral compounds play a rather insignificant role. This impression is strengthened by the fact that only about 5 per cent of a plant's body consists of soil-derived mineral compounds. The rest consists of air and water and of compounds derived from these two.

The recent investigations into the details of photosynthesis, however, have revealed that a special phosphate, adenosine triphosphate, which the plant produces from inorganic phosphate, is required in the basic process of using the energy of light to break down water into hydrogen and oxygen. On the other hand, three vitamins, viz., riboflavin (B_2), vitamin K, and vitamin C, likewise synthesized by the plant itself from various mineral compounds, are required for the production of the adenosine triphosphate. This, for the first time, proves the vital influence which soil-derived minerals exert on the basic life processes of a plant, and the small figure of 5 per cent assumes a new importance. Since the indispensable water likewise is taken up from the soil, and the carbon dioxide of the air has its origin largely in the organic matter decomposing in the soil, no doubt remains about the vital role played by the soil in this whole complex process.

Correct Proportion between Light and Dark Periods

The actual process of photosynthesis is not quite as simple as may appear from the preceding description. The resulting organic compounds are extremely complex in make-up, and some of the intermediate stages, in their formation within the plant, are still under study. The object throughout this presentation has been only to explain the most pertinent points. Detailed information on this matter must be obtained elsewhere. In order to round out this picture properly, however, it is still necessary to add that some of the fundamental reactions involved in carbohydrate formation proceed in the dark, not in light. Therefore, it is evident that night is quite as important as day for the healthy development of plants, and for this reason it is not possible to keep plants growing continuously by exposing them to artificial light without any dark period at all. The most favorable length of day and night varies with different plants, as well as with the state of their maturity.

10. ACIDITY AND ALKALINITY OF THE SOIL

Much has been said and written about the acidity and alkalinity of the soil, and the term pH of the soil has been used so freely, even in popular writing and lecturing, that most gardeners and farmers are familiar with it. The significance of soil pH is often heatedly disputed, and the claim is made again and again that acidity or alkalinity (as expressed in pH) is of little importance, provided that the soil structure and the soil nutrient content are suitable. Actually, chemical tests readily establish beyond any doubt that the reaction (the pH) of the soil very largely governs the availability of nutrients and also exerts an important influence on soil structure. In addition, the pH ranges, at which certain extremely important microorganisms of the soil find optimum conditions, are well known. Some extend into the acid range, others prefer an alkaline condition, many meet at a happy medium (page 113). The activity or inactivity, presence or absence, of the various microorganisms has a decisive influence on the availability of many important nutrients.

TOLERANCE OF PLANTS FOR pH RANGE

What clouds the picture and actually is at the bottom of all disputes is the tolerance of many plants for a fairly wide pH range, though this tolerance very rarely extends from a truly acid to a truly alkaline soil, and investigation has revealed in nearly all instances an optimum of strictly limited range at which each plant gives best results. Again confusing is the fact that climatic humidity has an influence on the optimum, and that in regions with high climatic humidity the optimum pH range for certain crop plants is likely to be somewhat higher than in regions with moderate humidity (page 114).

The actual implication of the expression "tolerance of plants" is frequently misunderstood by the layman. There are numerous instances where plants in nature live under certain conditions, not because they prefer them but because they are able to tolerate them. This ability to survive under adverse conditions frees these plants of the competition of other plants which would suppress them in more favorable habitats. As an example may be mentioned certain plants which inhabit salty mud flats on the seashore, where they even are subject to occasional inundation by sea water. These plants do not require salt, or if so, only in very minute doses. Most of them can readily be cultivated inland far away from the sea and entirely without salt, provided that physical, moisture, and pH conditions of the soil are suitable.

Acid-Loving Plants

The often recommended term *acid-tolerant plants* instead of *acid-loving plants* is, in most instances, inapplicable. Although plants may be found in a more strongly acid habitat than corresponds to their optimum, the optimum usually is not far away—rarely more than 1 or 1½ units of the pH scale. The large majority of plants, which in nature live in acid soil habitats, not only tolerate these conditions but actually require them, because their metabolic processes are adjusted to, and depend upon, an acid-soil reaction, so that they are unable to obtain the required nutrients from an alkaline or even a neutral soil. This fact is solidly supported by physiological investigation. (See also page 115.)

IMPORTANCE OF SOIL REACTION IN PLANT DEVELOPMENT

Whether the pH of a soil is an effect or a cause—a common source of argument—is rather immaterial. Though the H^+ ion concentration in itself is not solely responsible for all the phenomena which must be considered under the heading "soil reaction," the fact remains that it does exert a direct influence on the solubility of various nutrient compounds as well as on the facility with which dissolved nutrients are absorbed and used by plants. In consequence, pH measurements can serve to indicate soil conditions and, therewith, help appreciably in evaluating the productivity of a certain soil, relative to the type of plant to be grown. This is all that matters.

One must always keep in mind, however, that soil pH represents only one part of the whole soil picture. Its importance comes into focus only when it is considered in conjunction with all the other factors which influence plant growth. A coordination of the most important factors, including soil pH, will be found in Part VII.

THE pH SCALE

General Meaning

The determination of the acidity or alkalinity of a soil by measuring the pH value consists in establishing the concentration of the hydrogen (H^+) ions. Under the discussion of water (page 89) it was explained how the neutral point, pH 7, came to be established. A preponderance of H^+ ions results in acidity, which is expressed in pH figures below 7. A preponderance of OH^- ions results in alkalinity, which is expressed in pH figures above 7. At the same time it should be remembered that the pH scale, which begins at zero and ends at 14, runs inversely to the H^+ ion concentration or, in other words, that the lowest pH figure expresses the highest H^+ ion concentration, and the highest pH figure expresses the lowest H^+ ion concentration. The concentration of the hydroxyl (OH^-) ions increases in the same proportion in which the concentration of the hydrogen (H^+) ions decreases.

Comparison with Temperature Scale

The pH scale is an experience scale obtained empirically. Such experience scales are quite frequently employed in chemical or physical measurements. A good example is the centigrade—or Celsius—scale for measuring the temperature, which accepts the freezing point of pure water (at a barometric pressure of 760 mm) as 0°C (32°F) and the boiling point of pure water (at the same barometric pressure) as 100°C (212°F). Only between 0°C and 100°C is water a liquid. If ice is heated, the melted water maintains a temperature of 0°C until the last bit of ice has disappeared. Only then does the temperature begin to rise, and at 100°C the water begins to boil and to change into vapor. Again the temperature remains constant at 100°C until the last bit of water has disappeared. These phenomena offer an interesting parallel to the dissociation limits of water at pH 0 and pH 14. No change takes place above and below these points of the pH scale.

For investigations of the pH value of soils, only a limited part of the whole scale is of actual importance, since neither very high acidity nor very high alkalinity occurs in natural soils. It can be stated, in general, that the pH of soils which are suitable or can be made suitable for agricultural or horticultural purposes varies from 3.5 to pH 9.

FACTORS INFLUENCING SOIL REACTION

What causes acidity or alkalinity of the soil solution? This question touches upon the previously mentioned dispute as to whether soil pH should be considered a cause or an effect. The chemical reaction itself, whether acid or alkaline, is caused by the prevalence of either H^+ or OH^- ions, which are liberated through solution in water of various acids or bases present in the soil. What causes the presence or absence of some of these acid or basic substances, under varying conditions, is the point at dispute.

Climatic conditions have a decisive influence in determining whether acidity or alkalinity prevails. Topography, influencing drainage, enters the picture, and the chance presence or absence of certain mineral elements and other substances also plays its role. The relative stability of a certain condition, whether acid or alkaline, once it has developed, is caused by interacting influences which frequently are quite complex. That the ions of water themselves cannot be held solely responsible is evident from the fact that they are present in much too insignificant amounts. What else is involved?

Dissociation of Compounds Containing Hydrogen Ions

Any compound which contains hydrogen (H^+) will, when dissolved in water, add hydrogen ions to the soil solutions and thus will tend to render it more acid. Among acids which are frequently present in soils are sulfuric acid (H_2SO_4), hydrogen sulfide (H_2S), nitric acid (HNO_3), and, especially, carbonic acid (H_2CO_3). As can be seen from their formulas, all of these contain hydrogen, and it is understandable that the addition of their H^+ ions will render the soil solution more acid. Organic acids, such as fatty acids and humic acid (page 178), which originate from the decomposition of organic matter, act in a similar manner. The artificial acidification of soils through the addition of acid peat moss or other substances is described in Part VII (page 415).

Rain

Rain has a mildly acidifying effect on the top layer of soil, because it always carries a certain amount of carbonic acid as well as nitric acid and sulfuric acid. Testing soil immediately after a heavy rain will usually show a somewhat higher H^+ ion concentration (a lower pH value) than before the rain.

Formation of Acid Salts

Carbonic acid, which is present in all soils containing organic matter, cannot lower the pH below 5.9 if calcium carbonate ($CaCO_3$) is present, but it obtains additional importance from its participation in a process *called hydrolysis. (See page 156.) For instance, calcium carbonate ($CaCO_3$) forms, in the presence of carbonic acid through hydrolysis,* calcium bicarbonate [$Ca(HCO_3)_2$], and this dissociates in solution into Ca^{++}, CO_3^-, H^+, and $HCO^{-}{}_{3}^{-}$. Because of the fact that in this manner H^+ ions are added to the solution and the latter thus is rendered more acid, such salts as calcium bicarbonate are called acid salts. Iron, aluminum, and silica also form acid salts and quite frequently contribute to the acidity of mineral soils.

Residual Acidity of Fertilizers

Certain artificial fertilizers, such as ammonium sulfate and ammonium nitrate, likewise increase soil acidity. (See page 328.) The reason is that such ammonium compounds are subject to transformation by microorganisms and that, during this process, nitric acid (HNO_3) as well as sulfuric acid (H_2SO_4) are developed.

Addition of Hydroxyl Ions

Alkalinity of soils is caused in the same manner, through the presence of various bases (page 73) which add OH^- ions when they go into solution. Basic salts of sodium, such as sodium carbonate and also of calcium and magnesium are prominently involved. Like the acid salts, the basic salts are the result of hydrolysis, but, in contrast to the former, they add OH^- ions to the solution, rendering it more alkaline. Calcium plays an important role in soil alkalinity, and the liming of acid soils is a common practice. Its effect consists in replacing the H^+ ions with Ca^{++} ions in base exchange. (See page 71.) Ammonium, as well as various organic derivates of ammonium, causes a definitely alkaline reaction, which is the reason for the generally alkaline nature of fresh stable manure.

Soil Leaching

Changes of the soil pH frequently occur in nature through leaching. When bases, such as calcium carbonate or some of the above-mentioned other basic salts, are lost in drainage through leaching, the pH will gradually be lowered and may even change from alkaline to acid. The opposite may also happen, and humic acid as well as other acids may be washed out through repeated alternate flooding and draining. In this manner the pH of an organic soil may gradually rise, and the soil may not only approach neutral but may actually become alkaline. This phenomenon, with its attendant gradual change of the native flora, has been studied in detail, for instance, on the fens of Northern Ireland and Scotland.

Because of the changes which may occur naturally as well as those which may be induced artificially through the application of lime or of various fertilizers, a repeated checkup on soil pH is desirable and advisable.

TERMINOLOGY OF SOIL REACTION

To facilitate the correct interpretation of pH levels, Table 10.1 lists common descriptive terms for various states of soil reaction.

TABLE 10.1. SOIL pH RANGES AND DESCRIPTIVE TERMS

pH range	Corresponding term
Below pH 4.3	Extremely acid
" pH 4.3–4.9	Very strongly acid
" pH 5.0–5.4	Strongly acid
" pH 5.5–5.9	Moderately acid
" pH 6.0–6.5	Slightly acid
" pH 6.6–7.3	Neutral or nearly so
" pH 7.4–8.0	Alkaline
" pH 8.1–9.0	Strongly alkaline
Above pH 9.0	Very strongly alkaline

INFLUENCE OF pH VALUE ON AVAILABILITY OF NUTRIENTS

The significance of soil pH centers in its influence on plant growth. Since this influence is largely indirect and extends to several different, though interconnected, actions and reactions going on in the soil, these topics are discussed under separate headings.

Meaning of Availability

In all plant culture, efforts are concentrated on providing maximum fertility. For this reason, anything that may favor or hinder nutrient availability is of considerable interest. Before discussing the influence of pH in this connection, let us consider first what availability means. The mere fact that a required element is present in the soil is not sufficient, since plants can absorb it only when the compound in which it is contained is dissolved in water so that it is dissociated into ions. Solubility, on the other hand, depends upon the type of compound in which the element is present in the soil, whereas the type of compound formed in the soil depends very largely upon the presence of other ions in the soil solution. Soil pH exerts a strong influence on the solubility of many compounds, thus governing to a large extent the presence or absence of the various ions in the soil solution.

Iron, Manganese, Aluminum, and Phosphorus Availability

When the pH is low, iron, manganese, and aluminum compounds are readily soluble, and their ions, therefore, are active. Aluminum may even reach toxic amounts. As the pH rises (the soil becomes less acid, for instance, through liming), precipitation occurs, and less and less of the respective compounds becomes soluble, so that their ions become ever less available. Above neutral (pH 7), plants may have difficulty in obtaining sufficient manganese or iron even when these elements are present in available form, a condition for which calcium is largely responsible. (See page 318.)

Phosphorus, undeniably of great importance in plant nutrition, offers an excellent example of the influence of the pH on availability. (See page 210.)

Action of Sodium in Alkaline Soils

The presence of various carbonates, especially sodium carbonate, in strongly and very strongly alkaline soils (above pH 8.5) is of considerable significance, because it results in the replacement (in base exchange) of various cations, which are valuable in plant nutrition, by the undesirable sodium (Na^+) ions. This exchange takes place on the various soil colloids which hold the cations adsorbed. The most deleterious effect of this replacement concerns the soil organic matter. As stated previously (page 29), the sodium salt of humic acid is water soluble. In part, this is adsorbed by certain soil particles, giving the soil a dark color (black alkali soil), but the larger part is lost in drainage, resulting in impoverishment of the soil. (See page 178.)

INFLUENCE OF pH ON PLANT DISEASES

The various parasitic organisms causing plant diseases show, in laboratory culture, a very wide range of pH tolerance (often from strongly acid to strongly alkaline). Under natural conditions, however, they menace a plant's health only within a limited pH range. It appears that the health and vigor of the plants, which is highest under optimum pH conditions, is the deciding factor. The effect of the H^+ ion concentration on the disease, therefore, is only indirect, though pH measurements may serve to indicate favorable or unfavorable conditions.

The leaf spot disease of the garden iris (*Iris germanica*), which is caused by the fungus *Heterosporium iridis*, may serve as an example. Under laboratory conditions this fungus grows and produces spores at pH values ranging from 5 to 10, but it does not attack iris plants if the latter are growing in a soil with a pH of 7.5 or higher. This fact was beautifully illustrated by observations made on a plot of ground where two different types of natural soil happened to meet. On one part of this piece of land the soil was sandy and had a pH near 6, whereas the rest consisted of clayey soil with a pH near 8. The iris plants growing in the moderately acid sandy soil were seriously attacked by leaf spot, but those growing in the clayey alkaline soil—no more than a few hundred yards away—remained absolutely healthy, though the air must have been filled with the spores of the fungus which had every opportunity to drift over from the infected plots with the prevailing winds. That the garden iris finds its optimum growth conditions between pH 7.0 and 8.0 is a well-known fact. The greater vigor and better health of the plants undoubtedly helped them to resist the disease.

Banana wilt, known as *Panama disease* and caused by the fungus *Fusarium* (*Oxysporum*) *cubense*, is another case in point. This disease is most virulent at a pH range below 5.8.

Control

Similar conditions prevail with at least some of the other diseases affecting certain widely cultivated crop plants, though, unfortunately, not with all of them. It is evident that pH control cannot be of much help when the optimum for the development of the parasitic organism and of the plant is the same or nearly so. For example, the finger-and-toe disease, or club-root, of cabbage, cauliflower, and turnips which is caused by the fungus *Plasmodiophora brassicae*, appears to find its optimum conditions between pH 6 and 7, and germination of the spores is nearly inhibited at a pH value above 7.4. Unfortunately, the plants attacked by this parasitic fungus also thrive best at a pH slightly below neutral. Cabbage and cauliflower still give fairly good results up to pH 8, but turnips will not produce a good crop much above pH 6.5.

The common scab of potato, on the other hand (caused by several species of *Actinomyces*), causes most damage at pH values from 6.5 to 7.5. Since potatoes thrive extremely well at a pH of 5 to 6, pH control is helpful in this particular case, which explains why liming of the soil is likely to lead to trouble in potato culture. Unfortunately, another potato disease, called wart scab or black scab (caused by *Synchytrium*), finds optimum conditions around pH 5, which reduces the safety range to the vicinity of pH 6.

The situation is made worse through the frequent presence in the soil of still another parasitic fungus, *Rhizoctonia solani*, which causes black scurf of potatoes or rhizoctonia rot of various other plants, such as tomato, beet, and lettuce, and which is active from pH 4 to 7 or slightly above 7. In fact, it is most virulent around the neutral point. To inhibit it, a pH of at least 7.5 would be required which, however, is almost equally unfavorable for most of the plants which may be attacked, though tomatoes are alkali tolerant.

This limited discussion shows that there is a definite correlation between pH and the virulence of certain diseases. In certain instances it is possible to control a disease through control of the pH, but in others, as in the case of potatoes, pH control offers a safe method only if no more than one of the several potential enemies is present.

INFLUENCE OF pH ON SOIL MICROORGANISMS

Because of the very great importance of the microorganisms for successful plant culture they are dealt with separately in Chapter 4 and are mentioned prominently also in Part III. A discussion of pH cannot exclude them, however, since their activity is rather closely correlated with soil pH. A few examples must be given.

Ammonifying and Nitrifying Bacteria

What is probably the most significant activity of the soil microorganisms is concerned with the highly important element nitrogen and its availability to plants. This element undergoes a number of changes in the soil, which are caused by different bacteria and which start with the breakdown of proteins into ammonium compounds. These are changed into nitrites and thence into nitrates. The chain of these interdependent reactions must be continuous to assure a steady supply of readily available nitrogen to the crop plants.

Ammonification (the breakdown of proteins during putrefaction into ammonium compounds, which is caused by *Bacillus mycoides* and others) proceeds at a pH ranging from 3.5 to 7, with the optimum at 4.5 to 5.5. This, therefore, is an acid soil process.

Nitrification (the oxidizing of ammonium salts to nitrites and then to nitrates, which is caused by the bacteria *Nitrosomonas* and *Nitrobacter,* respectively) proceeds at a pH ranging from 4.5 to 11.9, with the optimum at 6.5 to 7.6. This, therefore, is essentially a neutral soil process.

The significance of these pH ranges lies in the fact that below pH 6 nitrification proceeds much more slowly than does ammonification. Actually, below pH 5.5, ammonium compounds accumulate, because they are produced faster than they are used. Between pH 6 and 6.5 ammonification and nitrification proceed at nearly equal speed, and the balance thus created is a very desirable one. Actually, this situation presents one of the main reasons why a pH between 6 and 7 is particularly favorable for many valuable crop plants.

The fact that the optimum pH ranges of these two types of bacteria do not coincide may seem strange, since the nitrifying bacteria are dependent on the products of the ammonifying bacteria. This divergence, however, has the vitally important consequence that the establishment of an equilibrium between ammonium and nitrate is favored, which tends to prevent quick nitrogen exhaustion.

Decomposition of Cellulose

One more example may be given. The decomposition of cellulose, which is accomplished by a number of microorganisms, proceeds most rapidly at a pH ranging from 6.8 to 7.5. Its lower limit is pH 6, and there is only slight action between pH 6 and 6.5. This explains why, in certain woodlands with slightly alkaline soil, leafmold hardly develops at all because of the rapid decomposition of cellulose. On the other hand, it explains the condition known as *springy turf,* which develops on slightly acid pastures or on moorland because of the very slow decomposition of organic matter in the soil layer immediately below the pasture grasses. Peat forms under still more acid conditions because of the absence or lowered activity of the bacteria which can decompose cellulose. (See also decomposition of lignin, page 167.)

INFLUENCE OF pH ON GROWTH OF HIGHER PLANTS

This all-important phase of pH influence has been left to the last, because it can hardly be examined in its proper perspective without consideration of the previously discussed aspects. As has been pointed out before, the importance of soil pH values in the life of higher plants is a much disputed subject among laymen. It is variously overstressed or ridiculed. As is so frequently the case, both extremes are wrong. Those who overstress the importance of soil pH in plant culture make the mistake of drawing the limits too narrowly. Many plants have a fairly wide range of tolerance, especially between pH 6 and 7.5, the most common soil pH range. They may find their optimum conditions around pH 6.5, but under cultivation, where competition is removed and where the plants are carefully tended—including the correction of nutrient deficiencies—they may still thrive very satisfactorily at a pH around 7.5. Serious trouble then develops only when the pH rises above 8 or falls below 6.

Climatic Humidity

The fact that climatic humidity has an influence on the optimum pH range for various plants must not be overlooked. It is stated, for instance, that in regions with relatively high climatic humidity, wheat gave best results at pH 7.3 to 7.8, and the optimum for sugar beet was at pH 7.6 to 8.5. Under conditions of moderate climatic humidity, the optima for the same plants were: wheat, pH 6.6 to 6.9; sugar beet, pH 6.6 to 7.3. Though these figures must be considered with due caution, since year-by-year variation in rainfall has to be taken into account and will make a difference, they do show that an influence is exerted. The many different actions of water, mentioned in previous chapters of this text (pages 84 and 85) are responsible. The important implication of the above figures is that observations made in one particular region cannot be generalized.

Plant Preferences

Those who ridicule the importance of soil pH or who consider it as of very minor interest are misled by the tolerance ranges of certain important crop plants, and overlook undeniable and well-proved scientific facts. In nature, even the occurrence of certain native plants can serve as an indication of soil conditions. Depending on what plants are present, one can draw definite conclusions on whether the soil is acid or alkaline. To avoid argument, it may be stated once more that not all plants are reliable in this respect. Some of them, however, are very strictly selective.

One of the best-known cases of such selectivity is that of rhododendrons and azaleas as well as various other plants of the same family, such as heath and heather, which not only prefer an acid soil but simply do not thrive under alkaline conditions. Why these plants are quite obviously tied to a definite type of soil reaction is a very intriguing question.

According to a series of investigations, carried out in Great Britain as well as in America, it appears that the answer may be found in the type of buffer system on which the metabolism of the plants is based.

The Functioning of a Buffer. The meaning of the word "buffer" (shock absorber) in this relation must be explained. Previously (page 110), it was pointed out that at various pH ranges a change occurs in the solubility of various compounds. A sudden and drastic change in pH, therefore, will have serious consequences by causing the precipitation and sudden unavailability of required elements. It is evident that a living plant organism cannot function if it is exposed to continuous ups and downs in this respect, and the cell sap, therefore, contains various organic or inorganic compounds which act as buffers by resisting change.

This resistance works by tying up the free OH^- and H^+ ions into various compounds, so that they cannot influence the pH. (Further details may be found in Chapter 15.) That buffering is always effective only within a certain pH range, must be realized, however. The range depends upon the type of acid or base which is present, and as soon as the acid or basic buffer is neutralized, the buffering action disappears. A sudden change then occurs which may have disastrous consequences.

Cell-Sap Buffering. Evidently the type of buffering system in the cell sap of a plant decides upon its preference for an acid or an alkaline soil or upon the degree of tolerance it may have for either or both. This does not mean that plants which by preference live on alkaline soils have an alkaline cell sap. In fact, they do not; the whole matter is not that simple. But some of these plants, at least, are known to have a buffering system based on phosphate, and such a metabolic system is open to injury by weak organic acids which are known to penetrate readily into living cells. A similar type of injury may occur on plants with a strictly acid buffer metabolism. If an acid organic soil, which is rich in iron, is heavily limed, the sudden raising of the pH of the soil solution will result in partly neutralizing the cell-sap buffering. Iron then may be precipitated within the cells, an effect which becomes apparent through what is called *chlorosis*. (See also page 14,)

The study of cell-sap buffering in correlation with the external pH is still a very young science, and by no means all is known about it. It cannot be doubted, however, that this line of investigation offers the first real promise of a solution to many puzzling questions concerning the soil pH preferences of plants. It appears that the establishment of a certain balance, in which the synthesis of hormones, vitamins, and enzymes is involved, and in which pH plays a major role, must be one of the key factors responsible for the dependence of many plants on a certain set of conditions.

Classification of Crop Plants According to pH Preference. Numerous lists have been prepared which enumerate plants according to their pH preferences. These will not be quoted here because such lists if not very complete and detailed are easily misleading. For many crop plants the optimum pH range depends upon, and changes with, the variety. Horticultural and agricultural varieties usually do not remain in favor for more than a few years, being then superseded by new ones of higher quality or greater resistance to disease, but for general guidance, a classification of crop plants is given in Table 10.1.[1]

TABLE 10.1. CLASSIFICATION OF CROP PLANTS ACCORDING TO pH PREFERENCE

1. *Acid-tolerant (pH 4–6)*	
Yellow lupines	pH 4–6 (or only 4–5)
Potato	Range pH 4.3–6.3; optimum pH 4.8–5.6
Swedes	Optimum pH 4.7–5.5
Timothy	Range pH 4.7–5.7
Oats	Optimum with some varieties, pH 4.8–5.4; with others, pH 5.5–6; (with some varieties even pH 7–8)
Tobacco	Range pH 4.5–6; optimum pH 5–5.6
Peanut	Optimum around pH 5.5
2. *Mesophilous, preferring slightly acid condition (between pH 5 and 7)*	
Flax	Range, depending on variety, pH 5–7 or 6.2–8, optimum around pH 6.5
Serradella	Optimum pH 5.4–6.5
Peas	Optimum of most varieties pH 5.5–6.4 (some varieties pH 6.9–7.5)
Meadow foxtail and many other pasture grasses	Optimum pH 5.6–6.4
Table turnips	Range pH 5.7–6.6; optimum pH 6–6.5
Rape	Optimum pH 5.8–6.7
Radish	Range pH 4.8–7; optimum around pH 6; some varieties have a range of tolerance up to pH 8.5, but their optimum still is near pH 6 or 6.5
Lima bean	Optimum around pH 6
Bush bean, pole bean, and broad bean	Optimum pH 6.2–7 (with some varieties, pH 6.9–7.5, or as low as 5.5)
Watermelon	Optimum around pH 6
Buckwheat	Range pH 3.9–7.7; optimum pH 6.7
Mangolds	Optimum pH 6–7
Corn or maize	*(Zea mays)* pH range 4–9; optimum depending upon the variety, usually between pH 6 and 7

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[1] Small, J., "pH and Plants," Baillière, Tindall and Cox, London, 1946.

TABLE 10.1. CLASSIFICATION OF CROP PLANTS ACCORDING TO pH PREFERENCE (Cont'd)

	3. *Alkali tolerant (above pH 6 and to some extent above 7)**
Wheat	General range pH 6–8; optimum for most varieties between pH 6.5 and 7.5 but with some as low as pH 5.3 or as high as 8
Rye	Range from pH 4.2–7.6; optimum depending upon variety but usually between pH 6 and 6.5 (with some varieties between pH 5 and 6)
Barley	Range 6–8; optimum with most varieties between pH 6.5 and 7.5
Sugar cane	Range pH 6–8; optimum pH 7–7.3
Rice	Optimum with most varieties around pH 7.9
Sugar beet	Range pH 6–8.5; optimum, depending upon variety, pH 6.5–7 or 7–7.5
Red clover	Range pH 5.5–8; optimum between pH 6 and 7
Other clovers, vetches, and alfalfa	Optimum pH 6.9–7.5
Lucerne	Range pH 6–8.2, optimum between pH 6.8 and 7.5 or higher
Beet, spinach, celery, and watercress	Range pH 6–8.5; optimum between pH 6 and 6.5

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* In this class, with a range from pH 6 to 8 and an optimum around or near pH 7, belong also the following crops cabbage, kale, cauliflower, parsley, parsnip, carrot, lettuce, tomato, pepper, cucumber, vegetable marrow, squash, melon, onion, leek, horse-radish, asparagus, upland cotton, and species of citrus

Table 10.1 can serve only as an indication of averages, and the previously mentioned fact that climatic humidity as well as the physical condition of the soil have an influence on the optimum must be taken into account also when a certain variety is chosen. Frequent soil testing, with carefully tabulated data from season to season, will be the best guide, and accumulated experience must do the rest. For garden culture it is futile to consult lists of pH preference ranges of plants with the object of adjusting the pH for each type of plant individually. This cannot be done. Such a list, however, will serve to explain why certain plants do not thrive in a certain garden, and these varieties may then be replaced by more suitable ones. In field culture, pH measurements will help to decide the selection of the crop plant most likely to give high yields on a given piece of land.

11. SOIL AGGREGATION

Soil pH has an important influence on soil structure, and, though not solely responsible, is intimately involved with the whole phenomenon of soil aggregation. Actually, soil aggregation, which results in a good crumb structure, is due to a combination of forces and factors, the four most important of which are: (1) the electrical condition of the inorganic soil colloids—in particular the clay colloids—and their behavior when partly loaded with various adsorbed cations, especially calcium, magnesium, and potassium; (2) the properties of certain organic soil substances, in particular those of humic acid and its salts; (3) the cementing action of certain mucilaginous substances, which result as intermediary products during the bacterial decomposition of carbohydrates, as well as the binding action of the mycelia of certain fungi; and (4) the forces of cohesion and adhesion active in the soil.

The effectiveness of the factors 2 and 3, in particular, is influenced by soil pH values. All four of these factors act in unison, complementing each other, and none, by itself, can produce lasting soil aggregation. To facilitate understanding, they will be discussed one by one.

ELECTRICAL CONDITION OF INORGANIC COLLOIDS

It will be remembered from the explanation of electrolytic dissociation (page 71) that substances which are dissolved in water dissociate into their ions, and that the latter bear an electrical charge. When colloids are wetted with water to the point of suspension, these minute particles likewise acquire an electrical charge (see page 75). Hydrosilicate colloids—clay colloids as well as silica colloids—acquire a negative charge. Certain other inorganic colloids, such as iron oxide or aluminum oxide colloids, become positively charged, but they are rather unimportant and will not be considered here, because, in comparison with the hydrosilicates, their amounts are always quite insignificant.

The electrical charge of the colloids has very important consequences, since it renders them sensitive to the presence of various ions which may carry an equal or an opposite charge (anions or cations), as the case may be. As was explained previously (page 72), electrical equals repel each other and electrical opposites attract each other. Therefore, colloids, which are equally charged, repel each other and remain dispersed.

Influence of Oppositely Charged Ions

When cations, such as H^+, Ca^{++}, Mg^{++}, K^+, and Na^+, are introduced into a suspension of negatively charged colloids, the cations are attracted and adsorbed by the colloids. This results in partly changing the charge of the colloids, which now attract each other and lump together. This phenomenon, variously called *flocculation, coagulation,* or *granulation,* is now generally termed *aggregation,* and this latter designation has been adopted here.

The most significant point in this action of the cations is that, when the colloids become completely saturated with any of them, they once more acquire an equal electrical charge and repel each other, which means that aggregation will be destroyed or at least impaired. Most dangerous in this respect is sodium (Na^+), though potassium (K^+) is a close second. Large surplus amounts of calcium (Ca^{++}) or magnesium (Mg^{++}) may likewise impair soil aggregation, though calcium (lime), if correctly used, is a valuable aid in producing a good crumb structure. The least dangerous cation is H^+, though at very high hydrogen-ion concentrations—which means when the pH is very low (below pH 5)—soil aggregation is nearly always poor.

The Important H^+ Ion and Its Influence

The fact that the H^+ ion also is involved brings soil pH into the picture. In consequence, pH measurements may be used as an indication of favorable or unfavorable conditions for soil aggregation. The most favorable level is near the neutral point or slightly below it, because this, in itself, signifies that the inorganic colloids are not saturated with any one of the various cations. What happens when the colloids do become saturated may be demonstrated by adding sodium carbonate (Na_2CO_3) to a suspension of well-aggregated clay colloids.

The Cause of Deflocculation

Sodium carbonate, in dissolving, dissociates into its ions Na^+ and CO_3^{--}, and the free Na^+ ions, by saturating the clay colloids, equalize their electrical charge, so that they now repel each other, destroying the aggregation. This phenomenon is frequently called *deflocculation* and has long been employed by potters, who add sodium carbonate (soda) to a tough, unyielding pottery clay in order to render it more plastic or moldable. In fact, it may be made so soft that it can be poured into the mold, and the potter then says that the clay has become "fluid."

pH Value as an Indicator of Conditions

The pH value of the soil is not, in itself, responsible for what happens, but it becomes an important aid by serving as an indicator of conditions. In the above case, the CO_3^{--} ions of the sodium carbonate are hydrolized simultaneously into undissociated carbonic acid (H_2CO_3). This has no influence on the pH value, but the H^+ ions required for this reaction have to come from the molecules of the water, and the free OH^- ions, which are left behind, will render the liquid more alkaline.[1]

It is readily understandable that an aggregation of colloids, which has resulted solely from the electrical reactions explained above, is by necessity rather fragile. It may be destroyed as quickly as it was formed. Fortunately, the other three factors, which were mentioned in the beginning, serve to increase greatly the permanency and resistance of the aggregates.

HUMIC ACID AND ITS SALTS

Colloid humus compounds, or, more specifically, humic acid and its water-insoluble salts—in particular calcium humate and magnesium humate—are amorphic and gluelike, as was explained in Part I. This gives them cementing properties eminently suitable for holding the inorganic colloids together. In addition, the extremely common calcium humate as well as magnesium humate appear to be able to adsorb both anions and cations, acting as polyelectrolites. In consequence of the varying electric charges, which thus result on their surface, they are able to attract and hold the originally negatively charged inorganic colloids which are always loaded in varying degrees with various cations such as H^+ and Ca^{++}. This electric attraction is of considerable importance in the production of stable soil aggregates. Since calcium humate is insoluble in water, soil aggregates which contain it remain stable even when suspended in water.

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[1] $Na_2CO_3 + H_2O = H_2CO_3 + 2Na^+ + 2OH^-$

sodium carbonate	*water*	*undissociated carbonic acid*

Calcium (Ca^{++}), as such, plays a rather important, though largely indirect, role in soil aggregation. In the first place it raises the pH value of an acid soil which results in creating more favorable conditions for the development of the most desirable microorganisms. This, in turn, as well as the addition of needed nutritional calcium, serves to accelerate the decomposition of organic matter, thus favoring the formation of the helpful calcium humate and of the later-mentioned polyuronides (page 122). The previously mentioned flocculation, resulting when Ca^{++} or other cations become adsorbed by the negatively charged inorganic colloids without saturating them, adds still further to the beneficial influence of properly calculated liming. (See page 410.)

Influence of Soil pH Values on Action of Organic Colloids

Soil reaction is of importance in this process, because the decomposition of organic matter proceeds too rapidly at high pH levels and too slowly at low pH levels to assure the continual presence of sufficient amounts of organic colloids. Colloid humus and, in particular, the useful calcium humate, therefore, are most freely present at a pH slightly below the neutral point (pH 7).

Interference by Soluble Salts of Humic Acid

How at high pH levels—in the true alkaline range—sodium will act as the villain, was indicated by the previously mentioned results of the addition of soda (Na_2CO_3) to a suspension of aggregated clay colloids. The formation of sodium humate, which is readily water soluble and which, therefore, is not only useless to assist in soil aggregation but is highly subject to leaching, further serves to destroy or to prevent soil aggregation at high pH levels.

Ammonium humate and potassium humate are equally water soluble. The former develops most readily at pH levels somewhat above 7.5 but generally is not common enough to cause trouble. When potassium is present in large surplus amounts, however, it is apt to replace calcium, and, under such conditions, potassium humate will become troublesome. The application of overlarge amounts of potassium fertilizer may in this manner result in serious damage to soil aggregation.

DECOMPOSITION PRODUCTS OF CELLULOSE AND FUNGUS MYCELIA

A further valuable aid in producing stable soil aggregation is presented by certain mucilaginous substances called *polyuronides* (levan and dextran), which result as intermediate products during the biological decomposition of cellulose and other carbohydrates. (See also page 165.) The cementing properties of these substances are as important as the netlike mycelia of the fungi which produce them. The fungus mycelia, which are readily discernible under the microscope, penetrate and surround the soil aggregates, holding the crumbs solidly together and greatly increasing their water stability. The polyuronides are polyelectrolites, which means that they are able to adsorb anions as well as cations. In consequence, they can and do establish a sort of chain linkage between variously charged soil colloids which further increases their holding capacity in a soil aggregate.

COHESION AND ADHESION AS CONTRIBUTING FACTORS

Cohesion is the sticking together of small particles merely because of surface tension, and its force is governed by the size of the surfaces which touch each other in relation to the masses which are involved. It is evident that the smaller the particles are, the more intimately will they touch, and, since the thin platelike mineral colloids (clay) have relatively large surfaces in comparison to their minute mass, cohesion exerts a strong force upon them.

Adhesion is caused by a film of liquid covering the particles. As far as soil is concerned, this is water. The force involved is the tension which develops on the border line between liquid and solid. An example is the fine sand of the seashore, which, when dry, cannot be balled together, no matter how fine it is or how hard it is pressed. When moistened, however, such sand can be pressed into various shapes, and it will stick together until it gets dry again, when the sand grains separate once more. This is true adhesion, cohesion being absent.

Pure clay on the other hand, which has much smaller particles, can be pressed together even when dry, showing true cohesion. When moistened clay is formed into a ball and subsequently dried until only the hygroscopic water remains, its particles hold together with considerable firmness, and the shape which has been given to it is maintained because of the combined forces of cohesion and adhesion. Thus, soils containing clay produce a much more durable aggregation than do those containing much sand, and it leaves no doubt that the size of the soil particles is an important factor in soil aggregation. Coarse particles can adhere to each other only when moist (adhesion), fine particles can stick together also when dry (cohesion).

MEASUREMENT OF SOIL AGGREGATION

Because of the important advantages for plant culture and resistance to erosion inherent in a good crumb structure, numerous methods have been proposed which attempt to measure the degree of aggregation of a given soil. One of the best known of these methods is the one proposed by Yoder in 1936 (*J. Am. Soc. Agron.*, p. 337) which employs a nest of sieves of carefully graded mesh. The nest starts with the largest mesh, and the soil is gently shaken through these sieves under water. The water-stable aggregates remaining in the various sieves are then dried and weighed, which permits the determination of the proportion in which water-stable aggregates of varying size are present.

PROMOTION OF GOOD SOIL AGGREGATION

Correction of the pH

The soil reaction, as has been shown, is of considerable importance, and the soil pH value should be checked carefully and repeatedly. In general, a pH of 6.5 to 7.2 is most favorable for soil aggregation, though fairly good aggregation is sometimes found as low as pH 5. Above pH 7.5 good soil aggregation is usually found only in alkaline organic soils, where it appears to be maintained mainly through the action of certain fungi.

Addition of Organic Substances

The importance of humic acid, especially of calcium humate, suggests the incorporation of organic matter, and this is indispensable when the structure of a heavy clay soil or of a light sandy soil is to be improved. Peat moss is an excellent material for this purpose, though acid peat moss must not be applied to a soil which is acid already, for this will further lower the pH. Various other materials, such as dead leaves, spent hops, ground-up corncobs or peanut shells, and even sawdust, may likewise be used if they are readily available and provided that proper precautions are observed. (See pages 168 and 277.) All of these materials contain not only lignin, which is required for the production of humic acid, but also cellulose, which, through biological decomposition, provides the above-mentioned mucilaginous substances (polyuronides). The plowing under of alfalfa or of strawy manure serves in a similar manner.

Moisture

It is evident that small soil particles can move toward each other in order to aggregate only in the presence of a certain amount of moisture. Besides, they become charged electrically only when they are wetted with water. Therefore, a moderate and steady soil moisture favors aggregation. Aggregation cannot be produced in very dry soil, but it may be maintained for quite some time under dry conditions if the crumbs were well stabilized before the soil became dry. The microorganisms, which have to decompose the organic matter in order to produce humic acid, likewise require a certain amount of moisture, though too high a water content is as detrimental for their development as when the soil is too dry. (See page 197.)

Cultural Methods

Annual plowing followed by frequent cultivation tends to lower soil aggregation gradually and may even destroy it eventually. Increased drainage and evaporation are largely to blame for this, though the accompanying aeration of the soil, resulting in too-rapid oxidation and decomposition of the organic matter, as well as mechanical disruption of the soil crumbs, are contributing factors. Such artificially created unfavorable conditions can be reversed by including in the crop rotation a period of continuous cover without disturbance. Two or three years of alfalfa or of pasture will aid materially in preserving a good soil aggregation.

Under garden conditions a mulch will serve very much the same purpose, besides protecting the soil against the force of falling raindrops. The latter not only cause actual loss of topsoil through splashing but are able also to destroy the aggregation of the upper soil layers.

Improvement of Saline Soils

The fact that highly saline soils, containing sodium chloride, will be particularly unfavorable for soil aggregation needs no further emphasis. Through the use of gypsum ($CaSO_4$), which results in replacing the sodium with calcium, and through irrigation, which will serve to leach out the sodium, considerable improvement in the soil structure can often be achieved. (See page 232.)

12. SOILS OF SPECIAL CHARACTER

ORGANIC SOILS

Most of the soils used for agricultural or horticultural purposes are so-called loam soils. All such soils are essentially of mineral origin, and whatever organic matter they contain represents merely an admixture. It is for these reasons that the constituents and properties of mineral soils have been treated in such detail. For a thorough understanding of soils in general, however, it is necessary to consider also organic soils, which, in contrast to mineral soils, consist mainly of decayed or decaying organic matter. Whatever particles of clay, silt, or sand some of them may contain have no part in their origin but represent admixtures usually caused by deposits from floods or runoff. Because of their difference in origin and composition, organic soils differ from mineral soils also in their micropopulation, a fact which is rather important and which must be considered whenever such soils are brought under cultivation.

Differences between Organic Forest Soil and True Peat

Two types of organic soils must be distinguished. One refers to the heavy layer of organic matter accumulating in standing forests where climatic conditions permit such accumulation, and the other includes the true peat soils. The separation between these two types is not always sharp, and the so-called "woodland peat," developing in forest swamps, as well as the "dry peat" of coniferous forests represent intermediate stages. The main difference as far as plants are concerned is that, under average forest conditions, the roots of the trees penetrate below the organic surface soil into the mineral soil beneath it, often to considerable depth. This permits them to benefit from the solutes infiltrating the mineral soil from the decomposing organic surface layer, while the organic acids which filter down assist in making mineral nutrient elements available. Roots of the low surface flora of the forest, consisting of herbs and small shrubs, may be, and frequently are, confined to the organic soil layer, but they benefit from the fact that the tree roots penetrate into the mineral soil beneath, because the dead leaves, needles, twigs, and fallen tree trunks continuously enrich the organic soil layer. In a true peat bog the vegetation is confined entirely to the surface, and no part of it penetrates beneath the peat.

Organic Forest Soils

Accumulation of Humus. It has been estimated that, in an average forest of medium age, from 1 to 2 tons of organic matter per acre drop to the ground yearly. How much of this rather large amount decomposes in autumn, before severe frost stops the process, as well as afterwards, from spring thaw until summer, depends on circumstances among which climatic conditions are often decisive. In the tropics and subtropics and also farther north in deciduous forests on more or less alkaline soils, most of the fallen leaves disappear within this 12-month period. Wood takes much longer to decompose, but a true leafmold layer of appreciable thickness may not develop at all. The decomposition products under such conditions are quickly incorporated in the mineral soil beneath, the humus materials infiltrating in colloidal suspension sometimes to a depth of several feet. The turnover of released plant nutrients then is rapid, though considerable reserves may be built up in the mineral soil itself.

Elsewhere in the Temperate Zones (North Temperate Zone and South Temperate Zone), especially on neutral or more or less acid soils, decomposition of the organic litter proceeds much more slowly, which results in surface accumulation. In the tropics or subtropics this may happen where a high water table prevents free soil-water movement.[1] Among the large variety of microorganisms which inhabit such forest litter and which, through their activity, maintain a favorable nutrient balance for the forest trees, aerobic fungi play a prominent role. Anaerobic nitrogen-fixing bacteria are usually also present in large numbers, whereas aerobic nitrogen-fixing bacteria are nearly or entirely absent. Earthworms, which are very active and plentiful in most deciduous or mixed forests—comparatively few or none are found in coniferous forests—play an important role in mixing the organic matter with the soil.

Average Soil Horizons in Deciduous Forests. According to the degree of decomposition, various soil layers may be distinguished.

NEWLY FALLEN LEAVES. Present as a layer only in the fall of the year.

LEAF MOLD OR OLD LEAVES. In this layer the structure of the plant

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[1] Wilde, S. A., "Forest Soils and Forest Growth," p. 43, Chronica Botanica, Waltham, Mass., 1946.

residues is still recognizable, and decomposition is incomplete. A rich population of cellulose-decomposing fungi is typical for this layer, and nitrogen is usually present only in the form of ammonium compounds.

MULL SOIL. The mull soil usually extends from 2 or 3 to 7 in. below the surface. Plant residues can no longer be distinguished, and—largely through the activity of worms and insects—the organic matter is mixed with inorganic particles and substances from the lower soil levels. This layer is richest in nitrogen-ammonium and nitrate, and contains anaerobic nitrogen-fixing bacteria.

TOPSOIL AND SUBSOIL. Under the "mull soil" follows the topsoil, which is the mineral soil more or less infiltrated with various solutes and with colloidal humus material from the organic layer above it. On loam soils this topsoil layer may be deep and is likely to be rich in plant nutrient reserves. Some of the most valuable agricultural soils in the eastern and central United States, in eastern Canada, in central Europe, and elsewhere are such former forest soils. The subsoil then commences where the infiltrated layer stops, and continues down to the underlying rock. Where a forest developed on cracked or more or less decomposed rock, the topsoil layer may be very thin, and no true subsoil may be discernible. In the northern parts of America and Eurasia, characterized by mild summers with rather equally distributed rains and by cold winters with abundant snowfall, podsolization is common. (See page 000.) This results in the production of a more or less leached and impoverished topsoil layer under the accumulated organic matter, followed by a more or less enriched layer farther down in the soil. It depends upon the progress of the podsolization process whether such soils are agriculturally usable, but many which are in such an advanced stage as to be quite worthless for agricultural purposes still are able to support excellent stands of timber.

As is evident from this short description, no generalization is possible. Whether organic matter accumulates or does not do so, and how it acts on the soil beneath, depends on a large variety of circumstances. Climatic zones are never sharply defined, and, in consequence, numerous intermediate conditions develop. The original composition of the soil on which the forest became established likewise varies from place to place, and the movement of the soil water as well as the height of the water table have an important influence also.

Soil Conditions in Coniferous Forests. In coniferous forests, such as stands of spruce and fir, the conditions are more clearly defined. The top layer, frequently several inches thick, consists of what is called *dry peat.* This represents several years' accumulation of dead needles and wood, with the structure still well recognizable but in varying stages of decomposition. There is no appreciable mixture with the soil beneath it, which commonly is sandy or stony and low in nutrient content. In northern coniferous forests the top humus layer usually is quite acid, with a pH near 4, while the soil underneath has a pH near 5. Pine forests usually occupy the poorest of all soils and often have only an extremely thin humus layer on top, the sandy soil underneath frequently being very acid, with a pH of 4 or less. The presence of tannins, resins, and terpenes inhibits the development of nitrate-forming bacteria, and such soils, therefore, always contain very little nitrate. Since the root fungi—mycorhiza—on which conifers generally depend for a large part of their nutrients require nitrogen in the form of ammonia compounds and cannot utilize nitrates, the significance of the symbiosis between conifers and fungi is evident.

CONIFERS UNDER CULTIVATION. The conditions just described can also serve to explain some of the difficulties encountered when conifers are planted for ornament. The root fungi required for the well-being of the conifers need a supply of raw humus, on which they live, and they are quite intolerant to serious drought conditions. The dry peat covering the surface under natural conditions preserves soil humidity, while aeration as well as penetration of rain water is not interfered with. In cultivation one should make every effort to duplicate these conditions by applying a mulch (a surface covering) of leaves, pine needles, straw, strawy manure, or wood chips. Contrary to common belief, peat moss is quite unsuitable for the purpose, since it absorbs a great deal of moisture, thus preventing aeration as well as the penetration of rain or irrigation water.

FOREST SOILS UNDER CULTIVATION. The study of forest soils is a science by itself on which considerable literature exists. The main purpose of this very condensed discussion was to point out the significance of the organic surface-soil layer which, under favorable circumstances and including the mull soil, may develop to a thickness of several feet. Because of its essentially high fertility, such a deep organic forest-soil layer frequently tempts the farmer. It is very perishable, however, once the forest is removed and will not last for more than a very few years when plowed and cropped.

When a forest is to be cleared away in order to put the land under cultivation, it is of the greatest importance to ascertain in advance not only the depth of the humus layer but, most of all, the depth and nature of the soil beneath it. Actually, it is the latter alone which counts and which will determine whether the fields thus gained from the forest will become hopelessly impoverished within a very short time or can, with proper treatment, be maintained at a steady level of continuing fertility. The agriculturally most valuable forest soils are the previously mentioned loam soils which show little surface accumulation of organic litter but are deeply infiltrated with organic solutes. Many other forest soils, and quite frequently those which show the most tempting humus layer on top, are unsuitable for agricultural purposes. They should be left in forest, since timber is the most valuable crop they are able to produce.

Peat Soils

Peat and muck may contain as much as 99 per cent of organic substance and, therefore, represent the most purely organic soils in existence. They occur in many regions of the earth but are most common in the North Temperate Zone, where peat bogs frequently cover extensive areas. It has been estimated that, in the United States alone, 79 million acres of land are covered with peat or muck. In the tropics, peat bogs are rare.

Formation of Peat. Normally, peat forms on land which is poorly drained so that water collects and stays there. What type of peat is produced depends largely upon the climate, since high humidity of the air and low temperature are most congenial for the development of certain mosses which are peat builders. Other factors exerting an influence are the pH value as well as the nutrient content and the depth of the water, since they govern the type of flora and fauna which develop and thereby determine the composition of the peat formed.

The reason peat forms in the first place is that plant residues accumulate, under the exclusion of oxygen owing to saturation with water, and remain incompletely decomposed. Anaerobic bacteria, which alone can live under such conditions, are unable to bring about complete decomposition. Besides, the high acidity, which usually develops, is inimical to those bacteria which are most efficient in the decomposition of cellulose. Formation of many peat bogs commenced probably during the ice age and is still continuing.

Types of Peat. Evidently, peat is not a uniform substance and by reason of its origin includes a large variety of different plant residues which are only partly decomposed. Furthermore, peat soils from different regions, which may have originated under very different conditions, are likely to vary widely in texture, chemical composition, and pH. Even one peat bog may include very definite strata formed during its development. For instance, when a shallow lake gradually fills in, the first deposits will consist of water plants and various algae (such as Diatomaceae), snails, and mussels, as well as silt and clay washed in by water from melting snow and rain. Reeds, bulrushes, and other bog plants will invade from the margins; alders and willows will reach out farther and farther; and finally mosses, such as species of *Sphagnum* and *Hypnum*, as well as various grasses and other plants will appear. Depending on conditions, the mosses, together with various Ericaceae, may even become dominant.

Types of peat are frequently classified, according to their structure, as fibrous peats and woody peats. It is much more appropriate as well as more instructive, however, to distinguish them according to their plant composition and origin as follows.

LOW-MOOR PEAT (MARSH, FEN, REED PEAT, SEDGE PEAT). Low-moor peat is found chiefly in river valleys or developing from shallow lakes and ponds. Such peat bogs usually are fed by underground waters which are rich in mineral salts and frequently contain calcium. They often drain slowly into lower regions. Their surface is more or less level or may be somewhat depressed in the center. They have their origin in reeds, rushes, sedges, certain mosses (*Hypnum*), many grasses, and some trees and shrubs. Sphagnum mosses are absent or rare. These peats usually are rich in proteins and in highly complex nitrogenous compounds which are synthesized by bacteria. In calcareous regions low-moor peat usually is underlain by marl. (See Part IV, page 221.)

HIGH-MOOR PEAT (MOOR, HEATH, SPHAGNUM PEAT). High-moor peats occur chiefly in cold or moderate climates with high precipitation or in the humid belts of high mountains. They derive their moisture mainly or only from rain and snow. If water seeps in from the sides, it is low in mineral content. These peat bogs are frequently higher in the center than on the sides, which gives them the outline of a watch glass, and they have their origin mainly from sphagnum moss. They may develop on top of low-moor peat or forest peat or directly on sand, clay, or rock. These peats usually are poor in minerals and contain very little calcium. They are frequently very acid, and, because of this condition which suppresses nitrifying bacteria, ammonia accumulates, held adsorbed by the organic colloids.

FOREST PEAT (WOODLAND PEAT, TRANSITION PEAT). Forest peat is found in permanently wet places inhabited by various trees and shrubs. This type, as the name "transition peat" indicates, is not very sharply defined and may show considerable variation in composition and reaction, depending mainly upon whether deciduous or coniferous trees predominate or whether one or the other is absent. The type of moss which develops also has an important influence. The moisture of these peat bogs usually is derived partly from underground water and partly from precipitation. They develop frequently on the upper courses of rivers, giving rise to springs, but occur also in lowland forests.

SEDIMENTARY PEAT (LAKE PEAT, MUCK PEAT). Sedimentary peat is found usually in the lowest layers of a peat bog or is sometimes dredged up from the bottom of a shallow lake. It consists of more or less thoroughly decomposed peaty material formed largely of algae, various water plants, water animals, plant residues from the flora surrounding the lake, and particles of clay, silt, and sand. This type of peat is usually comparatively rich in minerals and, when exposed to the air, the carbohydrates, proteins, and fats which it contains decompose rapidly under the influence of bacteria. As a medium for plant growth it is distinctly superior to the other three less-decomposed peats.

NUTRIENT CONTENT. The chemical composition of peat varies considerably, depending upon its origin. Averages for inorganic constituents, obtained through ash analysis, are given in Table 12.1.

TABLE 12.1. REPRESENTATIVE ANALYSES OF THREE PRINCIPAL GROUPS OF PEAT, PER CENT*

Type of peat	Nitrogen (N)	Potassium (K_2O)	Calcium (CaO)	Phosphorus (P_2O_5)
Low-moor peat (sedge peat)	2.91	0.15	1.95	0.10
High-moor peat (sphagnum peat)	0.92	0.06	0.20	0.04
Forest peat (woody peat)	2.05	0.12	1.41	0.11

* Wilde, S. A., "Forest Soils and Forest Growth," p. 53, 1946.

As can be seen from the figures in Table 12.1, the nutrient content of peat in its natural state is quite low. The organic matter itself, however, which makes up as much as or more than 75 per cent of the mass, and which consists of such substances as carbohydrates (6 to 42 per cent), proteins (5 to 25 per cent), lignins (20 to 70 per cent), and fats and resins (2 to 8 per cent), must be taken into account.

Peat Not Completely Sterile. The nutrients contained in these substances are locked up in extremely complex compounds and are not immediately available to higher plants, but they are present, and it is evident that peat is by no means the dead and sterile matter which it so frequently is considered to be. It has even been claimed that peat has germicidal or antiseptic properties, which would mean that neither plants nor animals could live in it. That this notion is completely erroneous is proved by the fact that numerous fungi, bacteria, and protozoa are always present in peat and that their number and variety increase enormously as soon as aeration is provided by drainage. In fact, as soon as a peat bog is drained, ammonifying bacteria become extremely active, and as soon as lime is added, raising the pH, nitrifying bacteria appear. (See page 113.) The draining and liming of peat bogs results in a very significant over-all change in their microflora.

Cultivation of Peat or Bog Soils. Three reasons why most higher plants, especially crop plants, do not thrive on raw peat soils are (1) the high water-holding capacity of the organic colloids (page 29) which must be counteracted through drainage, (2) the frequently high acidity (pH 3.2 to 5) which must be corrected by liming, and (3) the lack of immediately available nutrients, in particular nitrogen, phosphorus, and potassium, which can readily be supplemented through the application of suitable mineral fertilizers.

Large areas of low-moor peat bog have been reclaimed for agricultural purposes in many countries, mainly by means of such remedial measures. Forest peats also are sometimes put under cultivation, whereas high-moor peat is employed mainly as an addition to other soils in efforts to improve their physical properties or to acidify them. It is used also as farm litter or as a carrier for commercial fertilizers. Sedimentary peat sometimes is dried and is sold packaged or in 100-lb bags, under various trade names, as a soil amendment for the use of the home gardener.

The great value of peat as a means of improving mineral soils lacking in humus, as well as of modifying overalkalinity, will be treated further in Part VII.

It can be seen from this short presentation that peat, accumulated by nature through thousands of years and available in enormous quantities, has considerable value and wide possibilities. Through proper treatment it may be changed into humus, greatly needed for agricultural and horticultural purposes. Realization of its value is constantly spreading, and its usage as a source of humus is expanding. The United States alone uses over 200,000 tons of peat annually.

PART III

Soil Dynamics—The Interacting Forces Within the Soil (the Living Soil)

INTRODUCTION

The discussion of the properties of the soil (Part II) has attempted to make clear that soil is by no means merely a dead mass, or a mixture of particles and substances, but that it is a living entity with very distinct attributes. Beyond doubt, it is subject to numerous forces (physical, chemical, and biological) which change it continually. The results of the influence of these forces are generally designated as "dynamic processes." To distinguish sharply between soil properties and dynamic processes is not possible, because the two influence each other so very intimately that it is often difficult to decide which is cause and which is effect. The separation has been made here only in order to facilitate understanding, and Part II of this book may well be considered merely as an introduction to Part III. Part IV is in many ways a continuation of it, leading on to Part V.

13. HISTORICAL INTRODUCTION

In order to complete the picture of the interaction of the various forces, those which have not been covered in Part II must be explained in detail. But, before doing so, their importance may be further underlined by giving a short historical description of the manner in which natural dynamic processes, influenced by human interference, have produced present-day soil conditions in the agriculturally most important regions of the globe.

INFLUENCE OF CLIMATE ON SOIL FORMATION

Tropical Forests

Anyone who has ever given any thought to the soil in general must have wondered about the enormous and seemingly inexhaustible fertility of the soil in the tropics, where vast areas are covered with a vegetation so dense that it is almost impenetrable. These tropical forests have existed for thousands and perhaps millions of years, and there is no sign of diminishing vigor. The secret is twofold. The main contributing factor is the very high amount of rainfall. The moisture-laden air, rising from the steaming jungles, condenses as it cools and thus is forced to discharge the surplus of water it carries in the form of rain. This is a continuous process, and for months on end it rains every day during certain hours. The second factor is organic matter which, because of the high temperature, decomposes very rapidly. Since the trees are never entirely bare but continually shed part of their leaves, there is an uninterrupted circulation of required nutrients, with endless storage and use alternating in perfect balance.

The tropical farmer has discovered how very fragile this balance is. As soon as the forest cover is removed, the organic matter disappears very quickly, and, because of the high rainfall, the soil becomes so much impoverished within a year or two that it is useless. The most fearful erosion usually is the result. It is mainly for this reason that regularly spaced shade trees have to be maintained for most tropical cultures.

Regional Distribution of Forests, Deserts, and Plains

A look at a terrestrial globe discloses somewhat to the north of the tropical zone—in the so-called subtropics—an almost continuous belt of deserts and near-deserts stretching through all the continents—Asia, North Africa, and southern North America. The deserts and near-deserts of Australia, South Africa, and southern South America offer a parallel in the Southern Hemisphere, though they are less extensive, owing to the absence of equally large masses of land. The origin of these desert regions must be traced to the prevailing winds which, after having been deprived of their moisture, descend here from the equatorial forests. The descending air warms up and expands. Therefore, it holds whatever moisture it may still contain, and, in consequence, rainfall is absent or very rare. Farther toward the north the deserts are usually followed by treeless plains (so-called steppes), with moderate rainfall and covered with grasses and herbs. Then come the temperate forests and finally, still farther toward the pole, the regions with more or less permanently frozen subsoil, the tundras, covered with scrub or only with low herbs, mosses, and lichens. Only the irregular outlines of the continents and the influence of hot and cold ocean currents prevent these zones from being perfectly regular.

The Glacial Periods

To understand how present soils have originated, it is important to keep in mind that only the equatorial zone has remained comparatively undisturbed since the first appearance of manlike creatures (toward the end of the period called Pliocene) ½ to 1 million, or possibly 5 to 10 million, years ago. All the other zones have been subject to considerable changes during recurrent glacial periods, when ice covered vast stretches of land for thousands or tens of thousands of years and then receded. North America was covered with enormous sheets of ice as far south as the New England states and Ohio, as well as westward to the Mississippi valley. So was Europe, as far as the lower Rhine and south to the Carpathian Mountains and Thuringia. Most of Great Britain likewise was glaciated as far south as the Thames Valley.

The advancing glaciers moved millions of tons of soil, as well as rock detritus and even boulders, from one place to another, often for hundreds of miles, and during the warmer interglacial periods the runoff waters from the melting ice carried the material still farther. Organic matter also was transported by the ice. During the long, warm preglacial period, trees and other plants, even tree ferns, had established themselves on all the continents as far north as the Arctic Circle. These or their more or less decomposed remains were engulfed by the glaciers. The moving ice ground them to bits and deposited them elsewhere. The so-called alluvial deposits, consisting mainly of marl, sand, and soil but rather rich also in organic substance, resulted in part from glacial runoffs and represent the highly fertile soils which are characteristic of the deltas of the world's largest rivers, such as the Nile, the Mississippi, the Ganges, the Brahmaputra, and others. Wind also contributed by transporting fine soil particles which were deposited as chance permitted, sometimes in deep layers forming the so-called loess soils.

Rhythmic Changes in Climate

Relatively minor but still very important rhythmic over-all changes in the world's climate—which have been traced by means of plant remains—occurred even after the last glacial period and during the so-called historical period (beginning approximately with the year 6500 B.C. and extending to the present time). Evidence has been accumulated which makes it certain that from approximately 6000 to 3000 B.C. the climate in large parts of the world was rather mild and more humid than it is now. Greece at that time was covered with magnificent forests, and the Sumerian civilization, and after that the Babylonian Empire, reached their highest development in regions of Asia Minor which now are largely reduced to desert. After 3000 B.C. the climate gradually became less favorable for plant growth, and from 500 B.C. to 500 A.D. there followed a considerably cooler period accompanied, apparently, by violent storms. This was succeeded by another 1,000-year period of gradually improving and then again deteriorating climatic conditions, which, around the year 1500 A.D., appear to have reached their lowest point. Extensive glacier formations in Iceland and in the European Alps developed at that time and have left readily recognizable traces. Weather records over the last 100 years are sometimes quoted as evidence that we are now once more on the threshold of a period of gradually moderating climatic conditions. Temperature measurements, registered over the last 50 years in various arctic regions of the world, show a slow upward trend. Gradual receding of the glaciers and advancement of the timber line toward the north seem to confirm this observation. Only the future can tell whether this actually is the case.

The brief outline of the changing climatic conditions during the last few hundreds of thousands of years should give at least an inkling of the enormous natural forces which have been at work to fashion and to form, to move and to mix, present-day soil. These were, in the main, the physical or mechanical forces which, together with those of chemical and of biological origin, will be further explained in the succeeding chapters. But, before proceeding to these explanations, it may be worth while to consider in equally short review the effects on the natural dynamic processes produced by the interference of man.

INFLUENCE OF THE DEVELOPMENT OF CIVILIZATION AND AGRICULTURE ON PRESENT-DAY SOIL CONDITIONS

Development of Civilization and Agriculture

According to the most recent discoveries and theories, civilization—the establishment of permanent housing in larger community settlements supported by agriculture—developed separately in far-distant regions of the world. These were the Near East (especially in Mesopotamia and Egypt), central Asia (in the Gobi desert), and South America (in northern Peru). Every one of these centers of ancient civilization is located in an arid or semiarid region. Why agriculture was first practiced on a large scale under such seemingly adverse conditions seems puzzling. The theory has been advanced that dry farming with irrigation was the only type of farming that could be carried out with the extremely primitive tools available before iron was known. All of these once mighty empires now have vanished from the face of the earth. What were the reasons for their disappearance? Taking the fatal folly of mankind into account, they were foredoomed to destruction from the beginning.

The Inca Empire in Peru was already in decline when the Spaniards arrived and wrecked it. The disintegration of the Inca-created economy would have proceeded more slowly and might have been less complete without the Spaniards, but, like the others, they undoubtedly also would eventually have destroyed themselves. It is true, though, that the Incas knew more about soil erosion and how to stop it than any other people in the world at that time. Many of their intricate terraces and irrigation works are in use to this day. Not enough is known as yet about the very ancient settlements, which have been discovered in what is now the Gobi desert (central Asia), to draw definite conclusions as to the reasons for their fate. The chances are that the course of events paralleled rather closely what happened to the empires of the Sumerians and Babylonians in Mesopotamia.

The Sumerians and Babylonians

The history of these latter civilizations has been studied in considerable detail, by means of extensive excavations and from the inscriptions which they left behind. Their rise and fall, as far as it depended on their treatment of the all-important cultivated soil, is not difficult to reconstruct. Since the agricultural practices, as they were developed in the Mediterranean countries, have much to teach—actually, they have had a powerful influence on present-day methods—it is well worth while to take a short look at them.

The dry farming of the Sumerians and Babylonians as well as of other Near Eastern people—such as the inhabitants of the old kingdom of Yemen of Queen-of-Sheba fame (located in southern Arabia and now buried under tons of desert sand)—was based on a very delicately balanced water economy. Their intricate system of dams, canals, and irrigation channels, which excavations have revealed at least in part, were marvels of construction.

The availability of water, however, depends largely upon the possibility of storage at the source. This means forest cover. Besides, when semiarid soils are deprived of their natural plant cover, no matter how scanty, and are disturbed by cultivation, the loss of water through evaporation is tremendous. That soil fertility is highly exhaustible, when it is not carefully and expertly guarded and conserved, should hardly need emphasis, but these ancient people did not know this. They regarded their natural resources as inexhaustible, and, in consequence, they wasted them most shamefully.

Forests Controlling the Water Supply. As their civilization developed, they made ever-more-serious inroads into the forests, which at that time still covered the various mountainous areas of the region, never bothering where and how they cut the trees nor how much other vegetation they destroyed in the process. It never occurred to them that these forests controlled their water supply. Troubles soon multiplied. The increasing populations required more food, and their covetous rulers led them in wars of conquest. The armies of the various kingdoms fell upon each other, and destruction of the irrigation works was one of the most favored modes of punishment which they visited upon each other. In vengeance they often denuded whole mountain ranges of their precious forests. The victors brought back slaves who now had to carry out the manual labor connected with irrigation. The oppressed slaves and the abused common people revolted against their rulers. During such periods of chaos the all-important irrigation works were neglected and fell into disrepair, resulting in silting of the canals. Increasing soil salinity, resulting from careless irrigation practices, caused crop yields in large areas to decline to starvation levels. Erosion, resulting in large-scale loss of topsoil, contributed to the over-all deterioration. In addition to all this, a very gradual change had occurred in the climate, which had become appreciably less humid than it was when the forests first were established on the now-denuded mountain ranges. The delicate moisture balance, which nature herself threatened to tip, was thus violently upset by the folly of man. Vast stretches of desert now cover these once-flourishing civilizations.

These happenings, as outlined, centered in Mesopotamia (now Iraq), but they were paralleled in other Near Eastern countries, such as Syria and Palestine, where now-denuded and eroded mountain ranges were formerly covered with luxuriant forests, and present-day deserts or near-deserts formerly were fertile country. Though swiftly told, this tragedy encompassed 4,000 to 5,000 years, and the lesson it has to teach is that the consequences of such fearful abuse of nature and its resources will always be visited upon following generations.

Greece

Not very different were the happenings which resulted in the almost complete despoliation of Greece, now one of the most fearfully impoverished of all countries, though no more than 4,000 years ago still covered with magnificent forests and with rich agricultural land in its valleys. As the population increased, more and more of the forest was removed, and the fields crept ever higher up the slopes of the mountains. This, in itself, is a very dangerous procedure, the consequences of which were still further aggravated by a type of subsoil farming which the Greeks practiced, consisting in plowing the fields very deeply three to five times during the winter. Great pride was taken in straight, very close furrows, and subsequent cross-plowing, obliquely to the direction in which the field had been plowed previously, was a common routine. It is known, from writings of Theophrastus, Hesiod, and Xenophon, that this practice was based on the belief that the only way to create soil fertility was to give the winter moisture a chance to penetrate as deeply as possible. Unfortunately, this assumption was only partly correct, and the procedure employed was definitely faulty, resulting in extremely serious erosion and rapidly increasing impoverishment of the soil.

As the Greek Empire grew in power, more and more of the grain required to feed the people was imported from the colonies—especially from Sicily—and the fields were turned into olive groves and vineyards.

Then came wars—at first with nations from the Near East, which, because of their worsening climate were pressing northward, then with others from north and west. These wars have continued with only short interruptions up to the present time. The people, always barely existing on the edge of starvation, have resorted widely to the keeping of goats, these worst of all despoilers which crop herbage more closely than any other animal, eating even the roots.

Thus the Greece of today cannot possibly raise enough food to maintain its own people. To restore it to at least near-self-sufficiency agriculturally may be possible but would require an enormous expenditure of labor and money. It would certainly take not less than 100 years to restore at least a part of the lost forests without which successful agricultural restoration is not possible. The large-scale reforestation now being undertaken by the Jews in Palestine may point the way also for Greece.

The Romans

The Romans, who took over the role of world leaders in civilization when the Greek Empire collapsed, were the first of all civilized people to understand the influence of climatic conditions on soil fertility.

Foundation of Modern Farming Practices. In Roman writings, for instance, appears for the first time the recommendation that on a steep slope the furrows should be spaced wider and should run crosswise (transversally) to the slope, not up and down, to prevent the soil from washing downhill. This is the classical prototype of the now so widely practiced contour plowing, though the Romans still drew their furrows straight. The works of such Roman authors as Columella, who wrote 12 volumes on the culture of a large number of crop plants and fruit trees, remain admirable to this day. Pliny, the elder, who lived during the same period as Columella (the first century after Christ), included in his 37-volume "Historia Naturalis" detailed notes on farming principles and recommended, among other procedures, the planting of alfalfa and lucerne. He explained that their roots had an effect similar to stable manure in improving the quality of the crop which followed. Naturally, he did not know why they had this effect.

Most remarkable in the writings of the prolific Roman authors is the clearly stated recognition—expressed for the first time in the history of man—that soil treatment must take climate into account and must, in fact, be governed by it, if soil fertility is to be maintained. Simple as this perception may seem to us today, it actually represents one of the most significant steps forward ever achieved in the development of agriculture.

The vast extent of the Roman Empire and the controlling influence on all phases of human activity which the Romans exercised wherever they went spread their wise agricultural doctrines far and wide. No doubt remains that the astonishingly deep insight into the complexities of plant culture which the Romans developed actually laid the foundation for most of our modern farming practices.

Forest Destruction. Unfortunately, neither the Romans nor those who preceded or followed them understood the tremendous importance of the forests in maintaining a healthy moisture balance as well as in holding the soil on steep hillsides. Forests often were thoughtlessly destroyed. As in Greece, the Roman Empire, in expanding, resorted more and more to the import of grain, with the result that its own native agriculture declined. Olive groves and grapes were planted widely, and the hills and mountains were denuded of their forests and converted into pastures, which, in turn, were allowed to be cropped to exhaustion. Large-scale erosion followed and resulted in the completely bare, stony hillsides now such a common sight especially in southern Italy. The Roman subjugation of Gaul (now France) likewise resulted in a terrific destruction of forests, the consequences of which are felt there to this day. The soils of Italy, however, were not as badly ruined as those of Greece. They appear to be rather durable in character and seem to have a great power of recuperation. Besides, the period of decline in Roman agriculture served in many districts as a sort of long-term fallow which gave the soil a chance to recover. An enlightened policy of reforestation, which is now being attempted with American help, should go a long way toward restoring Italy to a more nearly balanced soil economy.

The Dark Ages

After the Roman Empire collapsed under the attack of more vigorous people from the north, while it was weakened by internal strife and corruption, a period of general chaos—usually termed the Dark Ages—descended upon Europe, and most of the agricultural wisdom of the Romans was forgotten. A period of feudalism followed, during which innumerable knights, lords, dukes, and princes were the only landholders, while the farmers, who tilled the soil, were serfs or near-serfs without any rights whatsoever except those granted them by their immediate masters.

This resulted in a fearful abuse of the soil, since the oppressed peasant had to wring the largest possible yield from his fields with extremely imperfect means of maintaining the fertility of the soil. The almost incessant warfare of one lord against another or one city against another resulted in further senseless destruction of forests and fields. Cattle, which would have supplied manure for the impoverished fields, were the first possession to be stolen or wantonly slaughtered by the robber barons, and the invaluable topsoil, deprived of saving humus, was washed away in large-scale erosion.

The emergence from this welter was very slow, and not until the seventeenth century can real improvement be perceived in the attitude of the European farmer toward his soil. This renaissance appears to have had its origin in Flanders where many of the agricultural principles of the Romans were still followed. The practice of crop rotation, for instance, was introduced into England from Flanders during the seventeenth century and was hailed at that time as the greatest single contribution to British agriculture.

Modern Agriculture

Modern scientific agriculture can be said to have had its beginnings toward the end of the eighteenth and during the early nineteenth century, with the realization that soil, which is cultivated by man and has been deprived of its natural plant cover, requires systematic and intelligent care, based on scientific study and observation, if rapid impoverishment is to be avoided. Nature, as long as it has not been interfered with, establishes a balance, which can and usually does maintain soil fertility unimpaired almost indefinitely, but once man, the cultivator, has disturbed this delicate balance, the natural dynamic forces of the soil can no longer be left to themselves but have to be guided and kept under control. This realization—an enlargement upon the early Roman perception that soil fertility depends upon soil treatment as much as upon climate—may, perhaps, be considered as the basic truth which governs all modern scientific agricultural endeavor.

North America

The development of agriculture in North America need only be mentioned very briefly, since its history is largely repetitious. The European settlers brought with them their European practices of farming, which—though far from perfect—had been reasonably effective in Europe, but which were rather ill adapted to a country of fierce contrasts in temperature, of hurricanes and tornadoes, and of violent rainstorms frequently resulting in floods. All of these manifestations of nature are almost unknown in Europe. Soils, therefore, were plowed which should never have been broken, and vast forests controlling watersheds were cut bare or were carelessly destroyed by fire. Erosion on an absolutely frightening scale resulted. The "dust bowl" (Oklahoma and Kansas) of still-recent memory may be mentioned as one of the best-known examples. It has been estimated that approximately 282 million acres of farmland have been ruined and another 775 million acres have been seriously damaged through erosion in the United States alone. The loss of potential topsoil caused by wrong farming and lumbering practices still amounts to several billion tons annually.

The question, therefore, arises: What of the future? Certainly it is not possible to continue treating soil in this wanton fashion, or America will share the fate of Mesopotamia and Greece. Fortunately, it is not yet too late to change wasteful practices, and much of what has been lost can still be regained if there is no delay. But it is absolutely necessary to abandon many of the European farming practices and to employ methods which take the peculiarities of climate and soil conditions of this continent into full account. The attitude of the farmer and gardener toward his soil requires radical readjustment.

The scientific study of soil and its behavior, which has made giant strides during the last decades, has placed much new knowledge and many invaluable new tools at the disposal of the farmer. If these are used intelligently, man may yet become master of the soil, which so far he is not. This would at the same time make him, in truth, the master of his own destiny.

14. THE DYNAMIC SOIL PROCESSES

It has been frequently stated in the previous parts of this book that the various processes of physical, chemical, and biological origin are closely integrated and not only influence each other but, in many ways, actually depend upon each other. To describe and to explain these processes, it is necessary to consider them successively, one by one, but the reader should always keep in mind that actually they take place side by side or simultaneously and that they go on continuously.

DYNAMIC SOIL PROCESSES WHICH DEPEND UPON PHYSICAL OR MECHANICAL FORCES

The Science of Dynamics

The science of dynamics, as it is involved in the formation, change, and loss of soil, includes the study of the properties of motion (kinematics) as well as of the forces which cause the motion (kinetics). In fact, the science of dynamics may be defined as the study of the forces inherent in bodies at rest and in bodies in motion, or the study of energy at rest as well as in motion. The frequently employed term *forces of nature* refers to dynamic forces, and the various physical forces brought into action by climatic conditions are the very ones which now must be considered. In order to explain clearly the manner in which rocks are weathered and are changed into soil, it is necessary to define, first of all, what force is and where it comes from.

The Meaning of Force and of Stored Energy. Force, in the physical sense, is the impulse which produces a change in the motion or in the rest of a body; it is the impulse which either puts a resting body into motion or which accelerates or retards a moving body. The source of this impulse is the stored energy inherent in all matter. As an example of what is meant by the term *stored energy,* a lake located on a mountain will serve. The water in this lake possesses considerable potential energy because of its location in relation to the valley below. If an opening is created, which permits the water to follow its natural inclination to run down to the valley, the stored or dormant energy of the resting water is converted into the energy of motion (kinetic energy), which produces force and which, therefore, can perform work (for instance, turn a water wheel). Whenever a force acts against resistance and therewith causes a body to move or causes a moving body to move faster or slower or to cease moving, one speaks of work performed or work done.

Concerning the influence of climate on the formation of soil, two forms of energy in particular must be considered. These are the energy released in the transmission of heat and the energy stored by water and air. The effects of temperature especially are quite complex and, because of their vital importance, will be discussed in some detail.

Effects of Temperature on Rocks

Expansion and Contraction. It is a well-known fact that most bodies expand (increase in volume) as their temperature rises and that they contract (decrease in volume) at lowered temperature. That this expansion and contraction must have far-reaching consequences in rock weathering becomes obvious when one considers that most rock formations represent aggregates of different minerals which do not expand or contract uniformly but which, instead, change volume at different speeds (they have different expansion coefficients). Temperature fluctuations, therefore, cause conflicting pressures in the rock strata, which result in loosening them, thus producing fissures, cracks, and rifts.

Exfoliation. Another phenomenon, *exfoliation,* is caused by the fact that rocks, in general, possess a relatively low capacity for the conduction of heat. In consequence, when they are exposed to the heat of the sun for any length of time, their surface heats up to a much higher degree than do their deeper layers. This results in a scaling off or peeling away of the surface. It is evident that these processes, caused by temperature fluctuations, are basic factors in the disintegration of the primal rock, in the lithosphere. Since this disintegration still continues and will go on as long as a rock is left on earth, new supplies of potential plant nutrients become available continually in this manner.

SPECIFIC HEAT OF VARIOUS SUBSTANCES. The reasons for the conflicting pressures, which develop in rocks when they are heated, become still clearer when different types of minerals, rocks, and other substances are compared in regard to the amount of heat required to raise their temperature by 1°C. This amount of heat is termed the *specific heat* or the *thermal capacity* of a body. The measuring unit (unit of heat or calorie) is the amount of heat required to raise the temperature of 1 g of water from 15° to 16°C. This amount, therefore, is accepted as the equivalent of 1 calorie (cal). All other liquids or solids require less than 1 cal to raise their temperature by 1°, and they maintain this (specific) requirement of heat over different ranges of temperatures (or temperature intervals). Above or below these characteristic temperature intervals, their heat requirement changes. Incidentally, the fact that more heat is required to raise the temperature of a certain definite amount of water than is needed for an equal raise in temperature of an equal amount of any other liquid or solid provides a very important safeguard in plant life. Since from 75 to 90 per cent of a living plant's body consists of water, it offers considerable resistance to changes in temperature, which would be fatal if they were rapid. Table 14.1 lists a number of different kinds of rocks and other substances, each with its specific heat and the temperature interval to which the latter applies.

TABLE 14 1 SPECIFIC HEAT OF VARIOUS SUBSTANCES RELATED TO TEMPERATURE INTERVALS

Substance	Temperature interval, C	Specific heat, cal
Water	15–16	1.0
Kaolin (chemically pure clay)	20–100	0.24
Pig iron	20–100	0 1189
Basalt	20–100	0 20
Granite	12–100	0 192
Marble	0–100	0.21
Mica	20–98	0 2061
Quartz	12–100	0 188
Wood	–	0.42

The specific heats of different types of soil have likewise been determined and are shown in Table 14.2.

TABLE 14.2. THE SPECIFIC HEAT OF SOILS

Soil type	Specific heat, cal
Sand	0.19
Clay soil	0.21
Limestone soil	0.25
Garden soil (loam)	0.27
Organic soil	0.26
Peat	0.25–0.48

Soil Temperature

Factors Influencing Soil Temperature. The great importance of soil temperature derives from its profound influence on *all* dynamic soil processes, including the chemical reactions and biological processes discussed in succeeding chapters. The main source of heat for warming the soil is, of course, the energy of the sun's rays (insolation), the effectiveness of which depends upon the following factors:

COLOR OF THE SOIL. Dark-colored soils warm up more quickly because of their greater capacity for absorbing the sun's rays, which are largely reflected into the atmosphere by light-colored soils.

PLANT COVER. Plant cover acts as an insulating layer, retarding the warming of the soil surface. On the other hand, plant cover likewise retards the loss of heat when the air is cooler than the soil. The density of the plant cover—densest under prairie conditions—determines the degree of insulation afforded. The seasonal leaf fall in a forest likewise results in an insulating soil covering. The gardener provides an artificial insulating layer by applying a mulch to his plants. This serves to prevent undesirable temperature fluctuations, keeping the soil temperature at a more constant level than bare soil can maintain.

SLOPE OF THE GROUND. Ground slope, and its position in relation to the direction of the sun's rays, influences soil temperature. According to a generally applicable physical law, the more nearly the inclination of a surface approaches a right angle to the direction of the heat rays, the more it heats up.

SPECIFIC HEAT OF THE SOIL. That soil always contains a certain amount of water needs no emphasis. However, Tables 14.1 and 14.2 have shown that water has a much higher specific heat (1 cal) than the average mineral soil (approximately 0.2 cal). This means that water requires a much larger amount of heat to raise its temperature than does dry mineral soil. In consequence, the more water a soil contains, the more slowly does it warm up. Actually, it has been found that a water content of 20 per cent raises the specific heat of mineral soil to 0.33 cal, whereas a water content of 30 per cent raises it to 0.38 cal. The greater heat requirement of a wet soil, which causes it to warm more slowly, represents at the same time a greater heat capacity, which means that, in theory at least, a wet soil also cools more slowly. This is not the case in reality, since other properties of the water act against it, as will become apparent from the following paragraphs.

Physical Factors Which Cause Loss in Soil Heat

Heat Conduction to the Atmosphere. This means the transfer of heat from warm soil to cooler air through contact. As is to be expected, heat can only be conducted from a body with a high temperature to one with a lower temperature, and the amount of heat transferred depends upon the difference of temperature between the two. Formulated as a physical law, these rather obvious facts are expressed as follows: The rate of transmission of heat by conduction is proportional to the temperature gradient. The speed of heat transmission between two bodies, which are in immediate contact with each other, depends upon the nature of these two bodies.

For instance, when a copper rod is connected to an aluminum rod and heat is applied to the free end of the copper rod, the free end of the aluminum rod will, in a short while, become very hot. This means that both of these metals are good heat conductors. When the copper rod is connected to a glass rod, the heat will hardly be transferred at all, and the free end of the glass rod will remain cool. Glass is a poor heat conductor, or a heat insulator.

As far as soil is concerned, the conduction of heat depends largely upon the amount of water present in the soil. Water is a good heat conductor; air is a poor one. In fact, the transfer of heat from soil to water proceeds 150 times as fast as from soil to air. Since water in the soil replaces the air, high water content is equivalent to low insulation. Soils with a high water-holding capacity and which, therefore, are inclined to stay wet—such as heavy clay soils—are, in consequence, at all times of the year cooler than soils with a low water-holding capacity, such as sandy soils.

Radiation. That heat radiation is something quite different from heat conduction becomes evident when one observes that happens when an electric heater is turned on in a cold room. Even at a distance of several feet, one will immediately feel the warmth of the heater, though the air of the room is still as cold as before. Since one is not in contact with the heater, there is no conduction.

This heat transmission is by means of rays, which the heater sends out as waves, and which are transformed into heat as soon as they strike an obstruction, such as a person sitting in the direct line of radiation. Contrary to the visible light rays of the spectrum, heat waves are invisible to the human eye (dark rays) and are of considerably longer wave length. Being located on the spectrum below the red rays, they are called infrared rays. All terrestrial bodies give off such radiation to the atmosphere. The amount of energy transmitted in this manner is rather high and, since the process is continuous also from soil to air, it contributes appreciably to the cooling of soil.

Evaporation. The transition from the liquid phase of water to the gaseous or, in other words, the conversion of water into water vapor, which is the essence of evaporation, is a process of considerable significance, especially since it has a profound influence also on many other dynamic soil processes. The speed with which evaporation proceeds depends mainly upon the temperature but is influenced also by the barometric pressure, the humidity of the air, and the nature of the soil.

The speed of evaporation determines the rate of cooling of the moist body (in this case the soil), from which the water is withdrawn. Why is evaporation accompanied by cooling? The reason is that energy is required to perform the work of turning water into vapor, and this energy is supplied in the form of heat by the body from which the water is evaporated. Loss of heat energy is, of course, synonymous with lowering of the temperature. Actually, evaporation proceeds at all temperatures, even below the freezing point, though then only slowly. As is to be expected, its speed increases with increasing temperature.

Besides the direct evaporation of water from the soil, the indirect evaporation, resulting from the exhalation or transpiration of water vapor by plants, contributes also to soil cooling. In fact, the amount of water evaporated by a living plant is astonishingly large, and the cooling effect which this evaporation produces is quite considerable. For example, weeds which are permitted to develop on seed beds during early spring, and which grow much faster than the crop plants, lower the soil temperature very appreciably; for this reason alone, they should not be tolerated. The enormous influence of evaporation on the heat balance of the soil may be surmised from the fact that, without evaporation, the temperature of the soil would rise so high on sunny midsummer days that no higher plants and few microorganisms could survive it.

IMPORTANCE OF DRAINAGE. This discussion of the physical effects of temperature makes it obvious that water is the main controlling factor. The reasons for the well-known fact that poorly drained soils are much colder in spring and remain cold longer than well-drained soils, have thus become clear. Since a certain optimal soil temperature is one of the main requirements for the germination of seeds, and since the failure of the soil to warm up sufficiently may result in a delay of precious weeks and even in the loss of seed, the importance of proper soil drainage to remove surplus moisture needs no further emphasis.

DYNAMIC SOIL PROCESSES RESULTING FROM CHEMICAL REACTIONS OR THE EFFECTS PRODUCED BY CHEMICAL FORCES

The vital difference between physical and chemical forces becomes apparent through the simple statement that the former do no more than change the position, shape, and size of the various rocks or other matter without changing their composition, whereas chemical processes result in the production of new substances which differ in composition from the parent substances. These chemical changes, however, must not be confused with the mechanical mixing of substances of different origin which is caused, for instance, by the physical force of wind and water, and which results in the production of soils of different physical composition. The individual substances, of which such a mixture consists, remain unchanged until chemical forces commence to act.

The Molecule

In order to be able to understand what happens when different substances act upon each other chemically, it is necessary to know that the various individual chemical substances consist of molecules (small particles). The term *molecule* is applied to the smallest units into which a substance can be divided, while still retaining its composition and properties. Such molecules are groups of atoms. The molecule of water, for instance, consists of 3 atoms, 2 of hydrogen and 1 of oxygen. This composition is expressed in its formula H_2O (water). The molecules of most other substances are much more complex. In chemical reactions—through the influence of one substance upon another (the exertion of chemical forces)—these atom groups are changed, resulting in the formation of new molecules and therewith of new substances.

Complete Combustion as an Example of a Chemical Process

One example may suffice to make the difference between mechanical (or physical) and chemical processes perfectly clear. When black coal is ground up in a mortar, one obtains a brownish powder. The molecule of coal—which is very complex and need not be given here—remains unchanged under this treatment. Only the physical form or appearance and the color of the material is changed. However, when coal is burned in complete combustion, which is the chemical process of carbon oxidation, a relatively small ash residue remains. The main mass of the material has been converted into gaseous substances, mainly carbon dioxide (CO_2) and water vapor (H_2O). The coal, therefore, has been transformed into several completely new substances, consisting of different atom groups (or molecules).

Aggregate Rocks as Source of Soil

The manner in which chemical forces were and still are active in converting rocks or mineral debris into soil will become more readily understandable from the following discussion, commencing with a short survey of some of the most common or most important types of rocks.

The large majority of all the primal rocks of the lithosphere (the crust of the earth) consist of aggregates (or combinations) of numerous, usually crystalline, minerals. In other words, many chemically individual substances of distinct crystalline form and of distinct chemical composition are combined in one rock mass.

Classification of Rocks

According to origin, rocks are placed in one of three main groups.

Igneous Rocks. Igneous rocks owe their origin and condition to a period of their history during which they were exposed to intense heat, reducing them to a more or less fluid condition. In cooling, they subsequently solidified into massive more or less crystalline bodies.

Sedimentary Rocks. Sedimentary rocks consist either of particles of decomposed igneous rocks or of animal and plant remains which settled

TABLE 14 3. SOME OF THE MOST COMMON TYPES OF ROCK WITH THEIR COMPONENT MINERALS

Type of rock	Name of rock	Main mineral components	Silica content, %
Igneous	Granite	Feldspars, quartz, micas, hornblende, augite, biotite, apatite, nephelite	70.18
	Basalt	Feldspars, augite, olivine, apatite, magnetite, ilmenite, zeolites	49.06
	Trachyte	Feldspars, augite, apatite, hornblende	60 68
	Porphyry	Feldspars, quartz, augite, biotite, hornblende, apatite	
Sedimentary	Sandstones	Quartz with cementing substances	78 66
	Clay shales	Clay, quartz, micas, chlorites, hematite	58 38
	Limestone	Calcium carbonate with variable quantities of magnesium carbonate (calcite and dolomite)	5 19
	Chalk	Calcium carbonate	
Metamorphic	Gneiss	Resulting mainly from more or less decomposed granite: quartz, feldspars, mica, hornblende	
	Schists and Slates	Very variable in composition and may result from gneisses, clay shales, or sandstones, or directly from various igneous rocks	
	Marble	Crystallized calcite resulting from limestone	
	Serpentine	Resulting from various decomposed igneous rocks, usually in combination with other sedimentary deposits, especially with calcite and magnesite	

from water. The pressure, resulting from the increasing thickness of the sediment, subsequently caused the particles to cohere or resulted in their being cemented together by other mineral substances in solution, such as colloidal silica, calcium carbonate, or certain iron compounds.

Metamorphic Rocks. Metamorphic rocks result from either igneous rocks or sedimentary deposits which subsequently became buried so deeply that, under the influence of heat and tremendous pressure, they became fused or at least considerably changed in form.

Table 14.3 lists some of the most common types of rock in each of the three categories and states the most important minerals of which they are composed. The significance of their average content of silica (SiO_2), given in the last column, will be explained presently.

Comparison of Composition of Solid Rocks and Surface Soil

The rock types listed in Table 14.3, as well as similar allied ones, represent the main solid constituents of the crust of the earth. A comparison of the chemical composition of solid rocks with the composition of average surface soil will reveal the changes which take place when rocks decompose and form soil.

TABLE 14.4. COMPARISON OF THE COMPOSITION OF SOLID ROCKS AND THE SURFACE SOIL, IN PERCENTAGES

Substance or Compound	Formula	Solid rocks, %	Surface soil, %	Changes in the surface soil as compared with solid rock	
				Increase, %	Decrease, %
Silicon oxide (silica)	SiO_2	59.77	84.67	41.7	
Magnesium oxide	MgO	3.74	0.27	—	92.6
Calcium oxide	CaO	4.86	0.41	—	91.7
Sodium oxide	Na_2O	3.25	0.49	—	85.0
Phosphoric acid anhydride	P_2O_5	0.28	0.09	—	67.5
Sulfuric acid anhydride	SO_3	0.28	0.09	—	67.5
Potassium oxide	K_2O	2.98	1.03	—	66.5
Iron oxide	Fe_2O_3	6.25	2.53	—	59.5
Aluminum oxide	Al_2O_3	14.89	6.73	—	54.9
Manganese oxide	MnO	0.09	0.06	—	33.3
Titanium oxide	TiO_2	0.77	0.66	—	14.3
Carbon	C	0.03	1.57	51.4	
Nitrogen	N	—	0.07		
Organic substance	—	—	2.61		

Table 14.4 is based on the publication of W. O. Robinson (*U.S. Dept. Agr. Bur. Soils, Bul. No. 122*), and the values quoted are averages. American soils only have been included, but it must be assumed that the averages cannot be very different elsewhere. The last two substances mentioned in Table 14.4 are not present in solid rocks but are formed only in the soil.

Silica

Table 14.4 shows that solid rock consists of about 60 per cent of silica and that all its other mineral constituents together make up the remaining 40 per cent. The surface soil presents a very different picture. Silica, as the most resistant end product of the weathering processes, has increased to approximately 85 per cent, and all the other soil constituents —including even the newly formed organic substances—amount to no more than 15 per cent of the total. Thus every soil contains considerable amounts of silica, usually in nearly pure form as sand or gravel or otherwise as a component of various minerals. In desert regions, where the weathering process is nearly completed, the soil may consist almost exclusively of silica. All the other constituents which, as shown in the table, have been lost from the soil to a greater or lesser extent, have either been deposited elsewhere as isolated sedimentary layers or have been washed into the oceans.

Sea Water

The influx of these vast amounts of mineral substances into the oceans is rather intriguing, especially when one considers that the composition of sea water is practically uniform all over the world. Table 14.5 lists the various salts contained in sea water in grams per liter, according to generally accepted standards.

TABLE 14.5. THE COMPOSITION OF SEA WATER

Salt	Formula	Grams per liter of sea water
Sodium chloride	$NaCl$	27.213
Magnesium chloride	$MgCl_2$	3.807
Magnesium sulfate	$MgSO_4$	1.658
Calcium sulfate	$CaSO_4$	1.260
Potassium sulfate	K_2SO_4	0 863
Calcium carbonate	$CaCO_3$	0.123
Magnesium bromide	$MgBr_2$	0.076

Origin of the Salt Content of Sea Water. It was formerly believed that the entire salt content of sea water came from the mineral salts which are carried into the oceans by the world's rivers. This supposition, however, is not reasonable, since many sodium compounds, especially sodium chloride, as well as bromides and sulfates in general occur on dry land in much too small amounts to account for the amounts contained in sea water. It is now presumed that most of the compounds are of volcanic origin, and this opinion is based on the fact that the fumaroles of volcanoes always bring forth large amounts of these very compounds. On the other hand, there is no doubt that the calcium, magnesium, and potassium fraction of the compounds present in sea water stem from the soil. The easily hydrolyzed compounds of iron, aluminum, and manganese are deposited as ooze at the bottom of the sea. (For hydrolysis, see page 156.)

Action of Chemical Forces on Composite Rocks

The question now poses itself: What are the chemical forces which are responsible for the great difference in composition between the rocks and the surface soil which originated from them?

The action of chemical forces on composite rocks such as those listed in Table 14.3 is, of course, by no means uniform but commences on those minerals which are most subject to conversion through chemical reactions, leaving the resistant rock components more or less unchanged. It was pointed out earlier that silica, especially in the form of quartz, is most resistant to chemical influences and is likely to remain unchanged for thousands of years.

Decomposition of Silicate Minerals. Very high on the list of the minerals important in soil formation stand the feldspars (from the German *feldspat*: *feld*—field, and *spat* or spar—a name given to various lustrous, easily cleavable, nonmetallic minerals). The general formula of feldspar is $M\,Al\,Si_3O_8$ (the M standing for either sodium, potassium, or calcium). Equally important are the micas, which are given the approximate formula $M\,Al_3\,Si_3O_{16}$ (the M standing for either hydrogen, sodium, or potassium, and the aluminum (Al) frequently being partially replaced by iron or magnesium. Fluorine also is frequently present.

Feldspars and micas, together with hornblende, augite, biotite, olivine, nephelite and others, are classified in the general group of silicate minerals. Their decomposition results first of all in the production of various types of clay, which is one of the most important of all soil components. Besides, these minerals are a primal source of the potassium, calcium, magnesium, iron, and manganese, which plants are able to obtain from the soil.

The chemical reactions responsible for the decomposition of the silicate minerals as well as for the conversion of the products which result are discussed in the following paragraphs. Although these processes must, by necessity, be described separately, they actually take place in nature more or less simultaneously. A few general explanations of the way in which the various reactions function must be given before the decomposition of the feldspars can be explained.

HYDROLYSIS. In the process termed *electrolytic dissociation,* which was explained previously (page 71), water serves only as a solvent and does not enter into the reaction. In hydrolysis or hydrolytic dissociation, the dissolving of the salt of a weak base or acid causes the water (H_2O) itself to dissociate beyond its normal degree of dissociation, and either one or the other of its two ions (H^+ or OH^-) enters into combination with the anions or cations of the acids or bases, forming undissociated acids or bases. This process may be further elucidated by the following equations:

$$\underset{\substack{\textit{sodium}\\\textit{carbonate}}}{Na_2CO_3} + \underset{\textit{water}}{H_2O} \rightleftharpoons \underset{\textit{sodium}}{2Na^+} + \underset{\substack{\textit{undissociated}\\\textit{carbonic acid}}}{H_2CO_3} + \underset{\substack{\textit{free}\\\textit{hydroxyl}\\\textit{ions}}}{2OH^-}$$

In this case the hydrolytic dissociation of the salt of a strong base (sodium carbonate) results in the formation of an undissociated weak acid (carbonic acid). The solution, shown on the right side of the equation, has an alkaline reaction because of the free hydroxyl ions (OH^-) which the reaction produces.

$$\underset{\substack{\textit{aluminum}\\\textit{sulfate}}}{Al_2(SO_4)_3} + \underset{\textit{water}}{H_2O} \rightleftharpoons \underset{\substack{\textit{sulfuric}\\\textit{acid}\\\textit{radical}}}{2SO_4^{--}} + \underset{\substack{\textit{undissociated}\\\textit{aluminum}\\\textit{hydroxide}}}{Al(OH)_3} + \underset{\substack{\textit{free}\\\textit{hydrogen}\\\textit{ions}}}{4H^+}$$

In this case the hydrolytic dissociation of the salt of a strong acid (aluminum sulfate) results in the formation of an undissociated weak base (aluminum hydroxide). The solution, shown on the right side of the equation, has an acid reaction because of the free hydrogen ions (H^+) which the reaction produces.

HYDRATION. Hydration is still another reaction caused by water and consists in the joining of undissociated molecules of water (H_2O) to the molecules of other compounds, which results in the formation of new substances. The most important of the various ways in which this process may take place are the following three:

Water of Crystallization. Many chemical substances take on water molecules when they are forced to crystallize through evaporation of a solution. How many water molecules are thus added to each molecule of the substance depends on circumstances such as the temperature or the concentration. An example is fused borax (a compound of sodium with boracic acid) which, in crystallizing, combines with water to form either one of four different hydrates. The pentahydrate of borax ($Na_2B_4O_7 + 5H_2O$) and especially the dekahydrate of borax ($Na_2B_4O_7 + 10H_2O$) are the most common ones.

Water Entering the Molecule of a Substance. In this process molecules of water are actually included in new larger molecules, resulting in the formation of a completely new substance. An example is the conversion of the valuable iron ore hematite into the more earthy limonite. The latter likewise serves as an iron ore. Bog iron ore is a variety of it.

$$\underset{\textit{hematite}}{2Fe_2O_3} + 3H_2O = \underset{\textit{limonite}}{2Fe_2O_3 \cdot 3H_2O}$$

Water Molecules or Hydroxyl Ions Combining with Oxides. The combination of hydroxyl ions with oxides of metals results in the formation of bases, whereas the combination of water molecules with oxides of nonmetals produces acids according to the following equations:

Oxides of metals

$$\underset{\substack{\textit{calcium}\\ \textit{oxide}}}{CaO} + \underset{\textit{water}}{H_2O} = \underset{\substack{\textit{calcium}\\ \textit{hydroxide}\\ \textit{(base)}}}{Ca(OH)_2}$$

$$\underset{\substack{\textit{sodium}\\ \textit{oxide}}}{Na_2O} + \underset{\textit{water}}{H_2O} = \underset{\substack{\textit{sodium}\\ \textit{hydroxide}\\ \textit{(base)}}}{2NaOH}$$

Oxides of nonmetals

$$\underset{\substack{\textit{anhydride}\\ \textit{of}\\ \textit{sulfuric}\\ \textit{acid}}}{SO_3} + \underset{\textit{water}}{H_2O} = \underset{\substack{\textit{sulfuric}\\ \textit{acid}}}{H_2SO_4}$$

$$\underset{\substack{\textit{anhydride}\\ \textit{of}\\ \textit{phosphoric}\\ \textit{acid}}}{P_2O_5} + \underset{\textit{water}}{3H_2O} = \underset{\substack{\textit{ortho-}\\ \textit{phosphoric}\\ \textit{acid}}}{2H_3PO_4}$$

Reversibility of Hydration Processes. All of the above examples are reversible, and the water which has been added can be removed again through the application of heat. This, however, does not apply to all hydrates or hydroxides. Since the appellations "hydrate" and "hydroxide" are frequently confused, it may be stated here that all compounds which contain molecules of water are hydrates; "Hydroxide" is reserved for those which contain groups of hydroxyl ions (OH^-), such as calcium hydroxide [$Ca(OH)_2$], ferric hydroxide [$Fe(OH)_3$], and sodium hydroxide ($NaOH$). As is evident from the above equations, the products of hydration have much larger molecules than do the original compounds. This increase in molecule size is, of course, equivalent to an increase in volume, which makes it obvious that the hydration of silicate minerals included in rock aggregates must, by necessity, cause such rocks to crumble into small pieces. Granite thus turns into granite gravel or even granite sand. Hydration, therefore, plays an important role in the decomposition of rocks.

Decomposition of Feldspars Through Hydrolysis and Hydration. The above preliminary explanations make it possible to turn now to a discussion of the manner in which feldspars decompose and form soil through the chemical reactions which generally are lumped together under the term *weathering.* Potassium feldspar (orthoclase), which has the formula $KAlSi_3O_8$, may serve as an example.

In hydrolysis the ions of water (H^+ and OH^-) enter the reaction and K (potassium) is split off in the manner expressed by the following equation:

$$2KAlSi_3O_8 + 2H^+ + 2OH^- \rightleftarrows \underset{\textit{undissociated}}{2HAlSi_3O_8} + \underset{\substack{\textit{potassium}\\ \textit{hydroxide}\\ \textit{dissociated}}}{2KOH}$$

$HAlSi_3O_8$ is an intermediate product in the process which leads to the formation of clay, and is generally present in the soil. The potassium hydroxide, which is formed at the same time, is immediately converted into potassium carbonate when carbon dioxide is present. This latter reaction, which is normal for the average soil, will be explained under carbonation.

Through hydration [the addition of the molecules of water (H_2O)], the intermediate product $HAlSi_3O_8$ is converted into the mineral kaolinite, the basic substance of all clays. This process, in which silicic acid is split off, is illustrated by the following equation:

$$2HAlSi_3O_8 + H_2O = \underset{\textit{kaolinite}}{H_4Al_2Si_2O_9} + \underset{\textit{silicic acid}}{4H_2SiO_3}$$

CARBONATION. In this important chemical process, which usually proceeds simultaneously with hydrolysis, the molecule of carbon dioxide (CO_2) enters into combination with one of the products of hydrolysis.

Since considerable amounts of carbon dioxide are commonly present in the soil atmosphere, carbonation, affecting a large number of minerals, not only contributes to the decomposition of rocks but is involved in various other dynamic soil processes also.

Conversion of Potassium Hydroxide to Potassium Carbonate. The potassium hydroxide (KOH), which is split off in the hydrolysis of potassium feldspar, is very unstable in the presence of carbon dioxide and is converted into the carbonate (K_2CO_3) as quickly as it is formed. When large amounts of carbon dioxide are present, potassium bicarbonate ($KHCO_3$) is formed. This is why potassium is hardly ever present in the soil in the hydroxide form, in spite of the fact that the latter is an unavoidable transition stage. The same applies to sodium and magnesium. If calcium hydroxide, which does not occur in nature, is added to the soil, it is likewise, and in exactly the same manner, subject to conversion into the carbonate.

HYDROLYSIS, HYDRATION, AND CARBONATION PROCEEDING SIMULTANEOUSLY. Returning once more to potassium feldspar. What happens, when both water and carbon dioxide are present in sufficient amounts, which is commonly the case in nature? Carbon dioxide and water together form carbonic acid (H_2CO_3), and hydrolysis, hydration, and carbonation proceed simultaneously or side by side. This may be expressed by the following equation:

$$\underset{\textit{orthoclase}}{2KAlSi_3O_8} + \underset{\textit{carbonic acid}}{H_2CO_3} + \underset{\textit{water}}{H_2O} = \underset{\textit{kaolinite}}{H_4Al_2Si_2O_9} + \underset{\textit{silicic acid}}{4H_4SiO_4} + \underset{\textit{potassium carbonate}}{K_2CO_3}$$

Both silicic acid (in its colloidal form) and potassium carbonate are highly water soluble and, if they are leached out completely—which in nature requires a very long time—very pure clay (kaolin) results. It is this type of clay, occurring in various parts of the world, which is employed in the production of fine pottery and chinaware. Under average conditions, at least some of the silicic acid will remain and will crystallize into silica or sand. Some of the potassium carbonate will remain also, the potassium (K_2O) being adsorbed by the soil colloids. Because the original amounts of potassium contained in the silicate minerals are extremely large and because continual replacement occurs as these minerals decompose, average soils contain relatively large amounts of available potassium.

Further Decomposition of the Clay Substance. Under the influence of acid water—for instance of water draining away from a bog or from the raw humus of a forest (see podsol, page 184)—the clay substance

($H_4Al_2Si_2O_9$) is subject to still further decomposition, until only the resistant silica (SiO_2) remains as sand. To explain this process, it may be assumed that sulfuric acid is acting on the clay substance. The reaction which will take place in this case may be illustrated with the following equation:

$$\underset{\substack{\text{clay}\\\text{substance}}}{H_4Al_2Si_2O_9} + \underset{\substack{\text{sulfuric}\\\text{acid}}}{3H_2SO_4} = \underset{\substack{\text{aluminum}\\\text{sulfate}}}{Al_2(SO_4)_3} + \underset{\text{silica}}{2SiO_2} + \underset{\text{water}}{5H_2O}$$

The highly water-soluble aluminum sulfate will be leached out, leaving only the resistant silica which remains as sand.

Oxidation and Reduction. Various other silicate minerals contain many other elements. In decomposition—for instance of olivine ($Mg_2Fe_2SiO_4$)—these other components, such as iron and magnesium, are separated in a manner which is quite similar to the process described for the separation of potassium from orthoclase. In the following, iron and manganese will be used to describe two other chemical processes which affect a great many elements and compounds and which, like hydrolysis, hydration, and carbonation, are actively participating in nature's development of the soil.

OXIDATION. As the name implies, this process consists in the addition of oxygen which may combine either directly with a metallic base or with a metalloid to form a so-called oxide. Calcium oxide (CaO) and sulfur trioxide (anhydride of sulfuric acid, SO_3) are examples. The latter combines with water to form sulfuric acid (H_2SO_4). (See hydration, page 156.)

Of particular interest are those chemical elements which have the ability to form several distinct stages of oxidation. This means that, depending on circumstances, they may take 1 or more atoms of oxygen into their molecule. Iron may form either ferrous oxide (FeO) or ferric oxide (Fe_2O_3), depending upon the amount of oxygen with which it has an opportunity to combine. Manganese behaves in a very similar fashion. The conversion of ferrous into ferric or of manganous into manganic oxide is illustrated by the following equations:

$$\underset{\substack{\text{ferrous}\\\text{oxide}}}{2FeO} + \underset{\text{oxygen}}{O_2} = \underset{\substack{\text{ferric}\\\text{oxide}}}{Fe_2O_3}$$

or

$$\underset{\substack{\text{man-}\\\text{ganous}\\\text{oxide}}}{2MnO} + \underset{\text{oxygen}}{O_2} = \underset{\substack{\text{manganic}\\\text{oxide}}}{Mn_2O_3}$$

A combination with acids results in the formation of the corresponding salts, as follows:

$$\underset{\textit{ferrous oxide}}{FeO} + \underset{\textit{sulfuric acid}}{H_2SO_4} = \underset{\textit{ferrous sulfate}}{FeSO_4} + \underset{\textit{water}}{H_2O}$$

or

$$\underset{\textit{ferric oxide}}{Fe_2O_3} + \underset{\textit{sulfuric acid}}{3H_2SO_4} = \underset{\textit{ferric sulfate}}{Fe_2(SO_4)_3} + \underset{\textit{water}}{3H_2O}$$

Manganese behaves in an exactly analogous manner. In nature these processes are somewhat more complex, and the above simplified equations are given only to facilitate understanding. As will be explained in the story of iron (page 239), many undisturbed virgin soils contain iron in the form of ferrous carbonate ($FeCO_3$) which, in the same manner as explained for the oxide, is converted into ferric carbonate when the soil is cultivated and therewith aerated.

REDUCTION. This process is the reverse of oxidation, since it consists in the removal of oxygen from a compound. The following equation may serve to illustrate it:

$$\underset{\textit{ferric carbonate}}{Fe_2(CO_3)_3} + \underset{\textit{hydrogen}}{2H} = \underset{\textit{ferrous carbonate}}{2FeCO_3} + \underset{\textit{carbon dioxide}}{CO_2} + \underset{\textit{water}}{H_2O}$$

In this case hydrogen acts as the reducing agent which removes oxygen from the iron compound to form water. Most of the reduction processes that occur in the soil are of biological origin, being caused by numerous anaerobic microorganisms which, in the absence of air, draw their required oxygen from various soil substances. In the case of iron, the reduction of ferric to ferrous carbonate has the further consequence that in the presence of surplus carbon dioxide—which means whenever organic substances are present—the readily water-soluble ferrous bicarbonate is formed, which is immediately available to plants. Both reduction and oxidation affect a vast number of substances, but both processes are reversible. Since they go on continually in any soil, their great importance and significance must not be underestimated.

DOUBLE DECOMPOSITION. There is still another chemical process which occurs very commonly in the soil but which is rarely understood in its full significance. This process, double decomposition, consists in an exchange of ions between two substances in such a manner that one of the resulting new substances is insoluble in water and, therefore, is precipitated. This reaction must not be confused with base and acid exchange (page 71) in which the soil colloids play the leading role. As will be remembered, the exchange of cations and anions in the latter case takes place between the soil colloids and a dissolved substance, the resulting new substance likewise being soluble. In fact, this solubility is a condition for base and acid exchange without which it cannot take place. Because of the manner in which it proceeds, base and acid exchange is gradual and continuous. Double decomposition, on the other hand, where dissolved substance acts directly upon dissolved substance, proceeds very rapidly and comes to a final stop within seconds. The soil colloids, in this case, have nothing to do with the process.

Double Decomposition Under Natural Conditions. The manner in which double decomposition takes place may first be explained as a natural process: the effect of hydrogen sulfide under anaerobic soil conditions. The biological decomposition of organic soil substances results in the production of hydrogen sulfide (H_2S) which is readily soluble in water. (See page 231.) The iron compounds most commonly present under anaerobic conditions are the readily soluble ferrous carbonates, such as ferrous hydrocarbonate [$Fe(HCO_3)_2$]. It may, therefore, be assumed that under such circumstances the following ions are present in the soil solution: Fe^{++}, HCO_3^-, H^+, and S^{--}. These ions, however, cannot exist side by side, because the ferrous and sulfur ions combine to form the water-insoluble ferrous sulfide (FeS). The reaction, the double decomposition, which results, may be expressed by the following equation:

$$\underbrace{\underset{\substack{\text{ferrous}\\ \text{hydro-}\\ \text{carbonate}}}{Fe(HCO_3)_2} + \underset{\substack{\text{hydrogen}\\ \text{sulfide}}}{H_2S} = \underset{\substack{\text{carbonic}\\ \text{acid}}}{2H_2CO_3}}_{\text{soluble}} + \underbrace{\underset{\substack{\text{ferrous}\\ \text{sulfide}}}{FeS}}_{\text{insoluble}}$$

As can be seen from the formulas, the ions of the compounds given on the left side of the equation have changed places. The insoluble FeS is precipitated.

Double Decomposition Under the Influence of Fertilizer Application. Of still greater significance is the process of double decomposition in cultivated soils, where, through the addition of the wrong type of fertilizer, especially when one has failed to take soil pH conditions into consideration, important plant nutrients may suddenly become insoluble and thus unavailable. An example is found in what happens when superphosphate is added to a soil which has a pH value below 6. At such a low pH level, the freely soluble ferric sulfate [$Fe(SO_4)_2$] is usually present, and with the addition of superphosphate the soil solution then contains the following ions: Ca^+, HPO_4^{--}, Fe^{+++}, and SO_4^{--}. Again, it is not possible for these ions to remain in solution side by side, because

HPO_4^{--} and Fe^{+++} together form insoluble ferric phosphate, which proceeds according to the following equation:

$$\underbrace{\underset{\textit{monocalcium phosphate}}{\mathrm{3Ca(H_2PO_4)_2}} + \underset{\textit{ferric sulfate}}{\mathrm{2Fe_2(SO_4)_3}} = \underset{\textit{calcium sulfate}}{\mathrm{3CaSO_4}}}_{\textit{soluble}} + \underbrace{\underset{\textit{ferric diphosphate}}{\mathrm{2Fe_2(HPO_4)_3}}}_{\textit{insoluble}} + \underset{\substack{\textit{sulfuric acid}\\ \textit{(neutralized}\\ \textit{immediately}\\ \textit{by calcium)}}}{\mathrm{3H_2SO_4}}$$

Once again, the ions have changed places, and the insoluble ferric diphosphate is precipitated. Soluble aluminum salts act in an absolutely analogous fashion. One reason for the very low availability or unavailability of phosphates at low pH levels is thus made plain.

Double Decomposition Employed in Chemical Analysis. Double decomposition is frequently employed in analytical chemistry, and one example, showing how this process serves in gravimetric determinations, may be given.

When sodium sulfate (Na_2SO_4) is dissolved in water, its Na^+ and SO_4^{--} ions are dissociated in the solution. When barium chloride ($BaCl_2$) is dissolved, its Ba^{++} and Cl^- ions likewise are dissociated. As long as these two solutions are kept separate, the ions remain dissociated, but, as soon as they are put together, a white precipitate of water-insoluble barium sulfate is formed.

The following equation will illustrate this process:

$$\underbrace{\underset{\textit{sodium sulfate}}{\mathrm{Na_2SO_4}} + \underset{\textit{barium chloride}}{\mathrm{BaCl_2}} = \underset{\textit{sodium chloride}}{\mathrm{2NaCl}}}_{\textit{soluble}} + \underbrace{\underset{\textit{barium sulfate}}{\mathrm{BaSO_4}}}_{\textit{insoluble}}$$

The important point is that the reaction is instantaneous and the exchange is complete. This means that all of the sulfate which was present is now precipitated, which makes it possible to determine very accurately the amount contained in a soil extract by weighing the precipitated barium sulfate.

Definition of Inorganic Soil

The preceding paragraphs, especially the description of the decomposition of the feldspars, may have left the impression that an inorganic soil represents nothing else than the end product of all these chemical processes. Such a conclusion would be a serious error, since true end products, such as pure sand or even pure clay (kaolin), are produced only under certain special circumstances. The soil which is employed to raise crops is, indeed, quite the opposite of an end product, and the very fact that the particles of which it is composed are subject to further decomposition and are not end products is an essential attribute of a fertile soil. The continuously proceeding decomposition of rocks and minerals into soluble substances represents invaluable reserves of plant nutrients which become available gradually. Without these immense reserves even the most skillful soil treatment could not prevent rapid and final soil exhaustion, and the restoration of an overcropped or mistreated soil—which has been robbed of most of its available nutrients—would be well nigh impossible.

DYNAMIC SOIL PROCESSES RESULTING FROM BIOLOGICAL FORCES

A general outline of the microorganisms which occur in soil, as well as of the various dynamic processes for which they are responsible, was given in Part I of this book. Further details on certain specific groups will be given later in Chapters 18, 22, 23, and 24. The following paragraphs merely stress a few additional facts which should be considered together with the dynamic processes of chemical origin. The close link existing between these two chains of processes will thus become more clearly apparent.

Biological and Chemical Processes Which Produce Identical Results

All considerations of the activities of soil microorganisms center, of course, on the organic soil substances which the vast majority of these organisms require either for their carbon supply or for both carbon and energy. Many soil microorganisms, however, obtain their oxygen from inorganic compounds, a process which has a vital influence on the availability of certain plant nutrients. Hydrolysis and oxidation, two other chemical processes, are likewise performed by microorganisms in the course of their life functions (their metabolism), though one should always bear in mind that the intervention of microorganisms is not required for these processes.

The latter statement once again emphasizes the fact that dynamic soil processes are immensely complex. It frequently happens that a purely chemical reaction starts the ball rolling and that microorganisms carry on afterwards, or vice versa. It happens likewise that the same process, resulting in the same end product, proceeds side by side chemically and biologically. This is the case with the oxidation of hydrogen sulfide (H_2S) to elemental sulfur (page 230) or with the precipitation of insoluble iron hydroxide (bog iron ore), a chain of reactions which includes hydrolysis, oxidation, and carbonation. (See page 238.)

The enzymes and ferments which microorganisms produce either inside their cells or as secretions and which are largely responsible for the various reactions and conversions caused by these organisms were described in Part II (page 79). The decomposition of carbohydrates, which so far has been mentioned only superficially, must be discussed further. Since the carbohydrates include cellulose and hemicellulose, and since the decomposition of these two extremely common organic substances results in the production of carbon dioxide as well as of humic acid and other organic acids, the processes involved are of greatest significance.

The decomposition of proteins, which likewise produces large amounts of carbon dioxide but which finds its greatest importance in the production of ammonia, is described in Chapter 18 and is mentioned again in Chapter 24. It may, therefore, be omitted in this discussion.

Biological Decomposition of Carbohydrates

Carbohydrates in soil organic matter are almost exclusively of plant origin, being contained in all kinds of plant remains. Cellulose and hemicellulose as well as starches, sugars, and pectins fall under this heading.

Cellulose, which is the main constituent of all living plant cells, consists solely of carbon, hydrogen, and oxygen, according to the general formula $(C_6H_{10}O_5)_n$, with n representing an as yet unknown figure. The decomposition of cellulose is accomplished by fungi, species of *Actinomyces*, and bacteria (aerobic as well as anaerobic), which break it up by means of hydrolysis through the excretion of enzymes, such as, in particular, cellulase.

The mucilaginous substances, such as levan and dextran, mentioned previously (page 121) as being important in soil aggregation, are formed as intermediary products.

Production and Breakup of Glucose. The completion of the hydrolysis under aerobic conditions, for instance in cultivated soil, results in the production of various sugars, such as cellubiose and glucose. Formation of the latter is shown in the following simplified equation:

$$\underset{\textit{cellulose}}{(C_6H_{10}O_5)_n} + \underset{\textit{water}}{nH_2O} = \underset{\textit{glucose}}{nC_6H_{12}O_6}$$

Since cellulose, as such, is completely insoluble in water, this process in the soil is strictly biological and cannot proceed without the above-mentioned enzymes. The part of the resulting glucose which is not assimilated by the microorganisms is rapidly broken down further by the same or by other organisms and is oxidized into carbon dioxide and water, according to the following equation:

$$\underset{\textit{glucose}}{C_6H_{12}O_6} + \underset{\textit{oxygen}}{6O_2} = \underset{\substack{\textit{carbon}\\ \textit{dioxide}}}{6CO_2} + \underset{\textit{water}}{6H_2O}$$

Production of Various Organic Acids. Glucose—or cellulose directly—may also be converted into various organic acids, such as acetic, butyric, and lactic acid or formic, acetic, and valeric acid. This happens most often under anaerobic conditions (when oxygen is lacking), but, since organic matter may, in plowing, easily become buried more deeply than is desirable, the reaction is not confined to bog conditions, where it is most common, but occurs to a certain extent also in cultivated soils. This type of conversion proceeds in several steps which may be expressed by the following equations:

(1) Hydrolysis:

$$\underset{\textit{cellulose}}{C_6H_{10}O_5} + \underset{\textit{water}}{H_2O} = \underset{\textit{pyruvic acid}}{2CH_3CO{\cdot}COOH} + \underset{\textit{hydrogen}}{2H_2}$$

(2) Reduction:

$$\underset{\textit{pyruvic acid}}{CH_3CO{\cdot}COOH} + \underset{\textit{hydrogen}}{H_2} = \underset{\textit{lactic acid}}{CH_3CHOH{\cdot}COOH}$$

(3) Biological breakup:

$$\underset{\textit{lactic acid}}{CH_3CHOH{\cdot}COOH} = \underset{\textit{butyric acid}}{CH_3(CH_2)_2COOH} + \underset{\substack{\textit{carbon}\\ \textit{dioxide}}}{2CO_2} + \underset{\textit{hydrogen}}{2H_2}$$

It must be understood that this chain of reactions represents only one of several possibilities. What happens in each case depends on prevailing conditions which may favor either one or another group of microorganisms. Under true bog conditions, for instance, methane gas (CH_4) is likely to be produced in addition to hydrogen and carbon dioxide.

Significance of Production of Carbon Dioxide. Details concerning the vital role played by carbon dioxide—one of the main products of carbohydrate decomposition—in various important natural processes will be found in Chapters 9, 15, and 24. A glimpse of the movement and utilization of carbon dioxide in the soil may be obtained from Table 14.6, which lists the carbon dioxide content of a field of winter wheat, month by month, as recorded at Rothamsted, England.

Table 14.6. Seasonal Variation in Carbon Dioxide Content of a Field of Winter Wheat

Month	Content of carbon dioxide, %	
	Manured field	Unmanured field
February	0.55	0.13
March	0.45	0.21
April	0.65	0.22
May	1.45	0.35
June	0.42	0.50
July	0.35	0.29
August	0.24	0.22
September	0.17	0.11
October	0.18	0.16
November	0.54	0.35
December	0.34	0.25

The differences from month to month are caused by the greater or lesser activity of the microorganisms under the influence of changing soil temperature, rainfall, and plant growth.

Lignin

Lignin is generally designated as the noncarbohydrate portion of the hardened or "lignified" plant tissue, because it can be chemically isolated and determined by destroying all the carbohydrates present. What is left then is the lignin. In view of the extremely important role which this substance plays in the household of nature, a few notes on what is known about it may be given here.

Formation of Lignin. The cell walls of plants during the early stages of growth consist of practically pure cellulose which has a carbon content of approximately 44 per cent. As growth continues, the cell walls harden through the deposition of lignin, which forms new compounds with the cellulose—so-called lignocelluloses. The latter have a carbon content of 47 to 50 per cent. Pure lignin has a carbon content of 61 to 65 per cent. Several theories have been advanced concerning the manner in which lignin is formed. It may develop from certain carbohydrates which are present in the cell walls—possibly through some type of dehydration—or it may be synthesized by the plants directly from sucrose.

Resistance of Lignin to Decomposition. The most significant point is that lignin shows a very high resistance to decomposition, and that only very few organisms are known to be capable of attacking it and using it as a source of energy. The most efficient of these latter are the higher fungi, those which are commonly known as mushrooms or toadstools, and, in particular, the bracket fungi which are attached sideways and without stalk to rotting logs or dead trees.

The peculiar phenomenon, sometimes observed in the forests, of seemingly intact tree trunks which, at a touch, crumble into a dark structureless powder, is caused by the almost complete decomposition and disappearance of the cellulose, with most of the lignin remaining behind. Such rotted wood usually contains up to 95% humic acid.

Colloidal Character of the Residual Lignin or Humic Acid. Cellulose and hemicellulose are decomposed in the soil by microorganisms long before the lignin is acted upon. The latter remains behind as a residual substance and actually represents the main and most permanent component of what is generally called humus. This lignin residue, the humic acid, is colloidal in character. There is evidence to prove that the presence of this substance favors the decomposition of cellulose, the fermentation of glucose, and nitrification. (See also p. 28.)

Sawdust as a Soil Conditioner. The great resistance of lignin to decomposition offers rather intriguing possibilities in horticulture, and the use of sawdust—a common surplus material which frequently is obtainable free of charge—for the amelioration of heavy soils is of interest. Why it is necessary to add a nitrogen fertilizer to sawdust used for soil improvement is explained in Chapter 18. If ammonium sulfate (or still better ammonium nitrate), superphosphate, and potassium are mixed with the sawdust, as much as a 4- to 5-in. layer of this mixture may be incorporated in the top 5 to 6 in. of soil.[1] In general, it is not advisable to plant immediately afterward, but if one waits 6 to 8 months after preparation of the bed, excellent results may be obtained. When acid peat moss is incorporated together with the prepared sawdust and a mulch of sawdust or wood chips mixed with ammonium fertilizer is maintained over the surface later on, clayey alkaline soils, in which rhododendrons and other Ericaceae do not thrive, may be made suitable for this kind of culture.

Sandy soils, lacking in humus, can likewise be greatly improved with sawdust, but under such conditions the possibility of overacidification presents a danger which must be watched for by means of pH tests. Fortunately, this can be corrected rather easily through correct liming and through neutralization of the residual acidity of the ammonium sulfate with ground limestone (110 lb of ground limestone for each 100 lb

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[1] Amounts of 115 lb of ammonium sulfate or 72 lb of ammonium nitrate/ton of dry sawdust have been computed as the required amounts. Per bushel of loose material, this would correspond to 0.8 lb of ammonium sulfate or 0.5 lb of ammonium nitrate. Allison, F. E., and Anderson, M. S. ("The Use of Sawdust for Mulches and Soil Improvement," *U.S. Dept. Agr. Circ. 891.*) (1951).

of ammonium sulfate). Spent hops after leaching, ground-up corncobs, ground-up peanut shells, cotton husks, and buckwheat shells, may be used in the same manner, provided that the same precautions are observed. (See also page 198 and Chapter 26, page 278.)

Indirect Role Played by Soil Humus

The fact that sawdust (as well as the similar materials mentioned above), which contains next to no plant nutrients, can actually achieve wonders in the soil simply by gradually turning into colloid humus serves at the same time to bring into clearer focus the indirect role which soil humus plays. Only when this role is fully realized will humus assume its rightful position as one of the required soil substances, and the undue exaggerations, which now are clouding the picture, will lose their appeal.

Hydroponics. In order to clarify the role of soil humus still further, it may be mentioned here that excellent healthy crops of full vitamin value may be raised entirely without humus by means of so-called soilless plant culture or "hydroponics." In this process, an inert and completely sterile material, such as vermiculite or gravel, is used simply to give the plant roots a hold, while all required nutrients are supplied in liquid form as dissolved inorganic substances, providing a carefully balanced diet. Complete information on procedure may be found in several excellent books on the subject. A sample composition of a nutrient solution is given in Table 14.7. Various others have been suggested and used successfully.

TABLE 14.7. SAMPLE COMPOSITION OF A NUTRIENT SOLUTION FOR SOILLESS PLANT CULTURE

Name of substance	Ounces in 25 gal of water
Ammonium phosphate (monobasic)	½
Potassium nitrate	2½
Calcium nitrate	2½
Magnesium sulfate	1½

PLUS MINOR OR TRACE ELEMENTS*
(1 cc of compound solution/liter of the above)

Name of substance	Formula	Grams/liter of water
Boric acid	H_3BO_3	2.86
Manganese chloride	$MnCl_2 \cdot 4H_2O$	1.81
Zinc sulfate	$ZnSO_4 \cdot 7H_2O$	0.22
Copper sulfate	$CuSO_4 \cdot 5H_2O$	0.08
Molybdic acid	$H_2MoO_4 \cdot H_2O$	0.02 (85% MoO_3)

* Iron tartrate (0.5%) is added by itself immediately before use at the rate of 1 cc/liter.

Though this type of culture cannot be employed generally, its practical value has been proved most impressively during World War II, when it permitted the raising of large supplies of fresh vegetables on Ascension Island, Iwo Jima, in Japan, and elsewhere, either where fertile soil was not available or where soil pollution presented a serious danger to the health of the troops, which had to be maintained.

15. THE BUFFERING ACTION OF SOIL

The term *buffer,* meaning shock absorber, is applied to solutions or suspensions which have the ability to offer resistance to a change in pH value. The decisive influence of soil pH on the solubility of various substances has been stressed in previous parts of this book (pages 110 and 121), and it has been pointed out that soil pH values between 6 and 7 are most favorable for soil aggregation as well as for plant nutrition. It is very important, therefore, to understand the forces active in the soil which set up a resistance to pH change. Not only is this helpful when one wishes to effect a change from an alkaline or highly acid condition to near neutral, but also when it is desired to stabilize the pH at a certain level.

The fact that each type of soil offers its own type of resistance complicates matters by making it impossible to give generally valid directions. If, for instance, one has a soil pH of 5 and wants to bring it to 6.5, one cannot compute offhand how many pounds of ground limestone per acre must be added to accomplish this. How much will be needed depends entirely upon the degree of resistance which the soil offers to the change or, in other words, on the manner in which it is buffered. The same applies to an alkaline soil which is to be acidified. Detailed directions for procedure are given in Part VII. This chapter is concerned only with explaining the chemical reactions involved.

IONS OF WATER AS GOVERNING FACTORS

As previously explained, the pH value, whether acid or alkaline, depends on which of the ions of water (H^+ or OH^-) is present in greater amount. If free H^+ ions are added to an alkaline solution (by introducing a substance which contains them), the pH value is lowered, because the proportion in which the 2 ions are present is altered in favor of H^+.

The same results are obtained in the opposite direction with an acid substance which adds free OH^- ions. Resistance to change—which is buffering—consists in tying up the free H^+ or OH^- ions through chemical reactions, so that they cannot affect the pH value. The manner in which this reaction proceeds is illustrated in the following examples.

STRONG AND WEAK ACIDS

Certain acids are the main agents of soil buffering, and two types of acids must be distinguished which are designated, respectively, as strong and weak acids. Hydrochloric acid (HCl), for instance, which was chosen to explain part of the pH scale (page 423), is at a pH range from 0 to 7 nearly completely dissociated into its ions, H^+ and Cl^-. Only when more acid is added, after the pH has been depressed to zero, does the additional hydrochloric acid remain undissociated. Sulfuric acid, nitric acid, and a number of others act in the same manner, and all of these are called "strong" acids. This type of acid has no buffering effect, for reasons which will presently become apparent.

Weak Acids as Buffers

The acids which do act as buffers are the weak acids, so called because they are never more than partly dissociated, no matter to what degree they are diluted with water. The weak acids most particularly responsible for soil buffering are carbonic acid and humic acids as well as their salts, though most organic acids, such as acetic acid, tartaric acid, oxalic acid, and citric acid, act in the same manner.

Acetic Acid. How the buffering mechanism works may be explained with acetic acid (CH_3COOH) which, when diluted with water, dissociates partly into its ions—the anion CH_3COO^- and the cation H^+. The important point is that undissociated acetic acid is always present also, besides the 2 free ions, no matter how much the acid is diluted.

When a small amount of a base—for instance calcium hydroxide [$Ca(OH)_2$]—is added to the diluted acid, one would expect the solution to become more alkaline, because the free H^+ ions of the dissociated acid will combine with the OH^- ions of the dissolved and dissociated calcium hydroxide to form water, according to the following equation:

$$\underset{\textit{acetic acid}}{2CH_3COOH} + \underset{\textit{calcium hydroxide}}{Ca(OH)_2} = \underset{\textit{calcium acetate}}{(CH_3COO)_2Ca} + \underset{\textit{water}}{H_2O}$$

This reaction should result in raising the pH value by changing the proportion of H^+ to OH^- in favor of OH^-. This does not happen, however, because, as soon as the free ions of acetic acid become tied up in the manner shown in the equation, more of the so-far undissociated acetic acid dissociates, maintaining the previous equilibrium. This process continues if more calcium hydroxide is added, and the pH value does not change until all of the acetic acid is converted into calcium acetate. The resistance to change up to saturation is buffering, and it is evident that acetic acid will produce a considerable amount of buffering toward a base.

BUFFERED ACETIC ACID. Still more intriguing though somewhat more complex is the resistance toward a lowering of the pH value, which may be built up in a weak acid through the addition of a strong acid. A mixture of acetic acid (CH_3COOH) and ammonium acetate (CH_3COONH_4) may serve as an example.

In a solution which contains both of these, the following ions will be present: those of acetic acid ($CH_3COO^- + H^+$) and those of the ammonium acetate ($CH_3COO^- + NH_4^+$).

Both substances, therefore, add CH_3COO^- ions to the solution. As stated above, however, acetic acid never does dissociate more than partly and, therefore, not more than a certain limited amount of free CH_3COO ions can be present in the solution under any circumstances. The result is that a certain equilibrium in the dissociation of the two substances is established, and the acetic acid is prevented from dissociating to its normal limit. Thus a solution of the two substances together contains fewer free H^+ ions (which remain tied to the undissociated acetic acid) and, therefore, has a higher pH value, than a solution of equal concentration of acetic acid by itself.

The significant point now is that such a mixture offers resistance to acidification or, in other words, is buffered against acids (a buffered acetic acid). What happens when a small amount of hydrochloric acid (HCl) is added may be illustrated by the following equation, which shows how hydrochloric acid reacts with ammonium acetate:

$$\underset{\substack{\textit{ammonium}\\\textit{acetate}}}{CH_3COONH_4} + \underset{\substack{\textit{hydrochloric}\\\textit{acid}}}{HCl} = \underset{\substack{\textit{acetic}\\\textit{acid}}}{CH_3COOH} + \underset{\substack{\textit{ammonium}\\\textit{chloride}}}{NH_4Cl}$$

The acetic acid, which results from this reaction, cannot dissociate because of the previous presence of acetic acid, which latter already is dissociated as far as the circumstances permit. In consequence, the H^+ ions, which hydrochloric acid normally adds to the solution and which would increase the latter's acidity, are tied up in the undissociated acetic acid, and the pH value remains unchanged. This buffering action continues until all of the ammonium acetate present is converted into ammonium chloride.

These two examples may suffice to explain the general mechanism of buffering as such. What are the forces which govern soil buffering?

SALTS OF WEAK ACIDS AS BUFFERS

The previously mentioned weak acids—carbonic acid, phosphoric acid, and humic acid—produce in the soil exactly the same type of buffering action toward bases as was explained for acetic acid. Still more important, however, are their salts, especially their very common calcium salts. These latter act toward strong acids, such as sulfuric acid, in exactly the same manner as was described for ammonium acetate and hydrochloric acid. They provide buffering until they are saturated. Toward weak acids their buffering is complete. This latter action is particularly important for plant culture in soil, and will be explained in further detail by means of a series of experiments.

The simple apparatus employed in these experiments consisted of a container holding water as well as the soil or other substance being examined. A rapidly rotating electric stirrer maintained the latter in suspension and prevented it from settling to the bottom. A finely porous distributor, made of fritted glass, was inserted in the container, permitting the introduction of carbon dioxide into the liquid in very fine dispersion.

Two electrodes—one glass and one calomel—were also inserted and served to register the pH of the liquid on the scale of the potentiometer.

Buffering Action of Calcium Carbonate (Limestone)

Effect of Carbon Dioxide on Calcium Carbonate. The buffering action of calcium carbonate ($CaCO_3$), a salt of carbonic acid (H_2CO_3), toward carbonic acid is of very great importance in nature, since it prevents undesirable overacidification of the soil.

The experiment to establish how this buffering works employed a saturated solution of *pure* calcium carbonate, into which carbon dioxide (CO_2) was introduced by means of the above-described apparatus.

A saturated solution of calcium carbonate (0.015 g/liter at 20°C), in the absence of carbon dioxide, has a pH value of 9.3.

When carbon dioxide is introduced into pure water (without calcium carbonate being present), it is converted into carbonic acid up to saturation, according to the equation $CO_2 + H_2O = H_2CO_3$. At normal barometric pressure and at a temperature of approximately 25°C, this has a pH value of 3.8 to 3.9.

When carbon dioxide is introduced into the saturated calcium carbonate solution, one will observe that the scale of the potentiometer adjusts itself rather quickly to the pH value 5.9 to 6.0, and that it remains at this point permanently, no matter how much more carbon dioxide is added. This means that the calcium carbonate solution is absolutely and completely buffered against carbon dioxide.

Calcium Bicarbonate and the "Requisite" Carbonic Acid. Responsible for this phenomenon is the fact that calcium carbonate combines with the carbonic acid to form calcium bicarbonate according to the following equation:

$$\underset{\textit{calcium carbonate}}{CaCO_3} + \underset{\textit{carbonic acid}}{H_2CO_3} = \underset{\textit{calcium bicarbonate}}{Ca(HCO_3)_2}$$

It is the calcium bicarbonate which has the above-mentioned pH value of 5.9. Naturally, one would expect that, as soon as all the calcium carbonate present is converted into calcium bicarbonate, free carbonic acid would develop and its free H^+ ions would lower the pH to 3.9. Calcium bicarbonate, however, can remain in solution only in the presence of a very definite surplus amount of undissociated H_2CO_3, which latter is termed the *requisite* carbonic acid. The above equation for the development of calcium bicarbonate should, therefore, be written more accurately as follows:

$$\underset{\textit{calcium carbonate}}{CaCO_3} + \underset{\textit{water}}{H_2O} + \underset{\textit{carbon dioxide}}{xCO_2} = \underset{\textit{calcium bicarbonate}}{Ca(HCO_3)_2} \cdot \underset{\textit{carbonic acid}}{nH_2CO_3}$$

The x in this equation stands for a surplus amount of carbon dioxide, and the n represents a very definite ratio (determined experimentally) between calcium bicarbonate and requisite carbonic acid. The significance of the requisite carbonic acid rests in the fact that the H_2CO_3 must reach the limit of its dissociation even before calcium bicarbonate can be formed. It will be remembered that weak acids never dissociate completely. Therefore, it will dissociate only to the amount required to convert the calcium carbonate into the bicarbonate. When this reaction is completed, no more dissociated carbonic acid can be formed, because the limit of dissociation was reached before the reaction commenced. Additional carbon dioxide will simply escape into the air and can have no further influence on the pH value.

The consequence of this process is that the carbon dioxide, which is produced by the microorganisms in the decomposition of organic matter and which is discharged by the plant roots, will result in acidification of the soil, but, as long as calcium carbonate is present, never below the limit of pH 5.9. Since, under normal conditions, it is most unlikely that sufficient amounts of carbon dioxide will ever be produced to continue the conversion of calcium carbonate into bicarbonate to the possible limit, the average result of this reaction will be a somewhat higher pH value (between 6 and 7).

Rising of the pH of Calcium-Rich Soils During Winter. After the growing season, when the crops have been harvested, the temperature declines, and the activity of the microorganisms diminishes, the carbon dioxide content of the soil quite naturally becomes lower than during summer. In consequence, less of the requisite carbonic acid is available, which results in partial reconversion of the calcium bicarbonate into calcium carbonate. This causes the pH to rise somewhat during winter, a phenomenon which, through repeated pH measurements, can readily be observed in largely inorganic calcium-rich soils. The fact that the highly water-soluble calcium bicarbonate is subject to being leached out by heavy autumn rains favors this rise of pH value.

Buffering Action of Calcium Phosphate

Calcium Bicarbonate Responsible for Buffering with Phosphates. This type of buffering likewise is based on the formation of calcium bicarbonate in a manner very similar to that described above. The fact that phosphoric acid (H_3PO_4) forms three individually distinct salts with calcium (see Chapter 19) introduces certain differences which are explained below.

An aqueous solution of monocalcium phosphate [$Ca(H_2PO_4)_2$], for instance, has a pH of 2.65, which makes it a much stronger acid than carbonic acid with a pH of 3.9. It is evident, therefore, that this particular phosphoric acid salt cannot be affected by carbonic acid. As stated later (page 209), however, if various basic substances, such as calcium carbonate, sodium carbonate, magnesium, or iron salts, are present in the soil, monocalcium phosphate is rather quickly converted into the diphosphate ($CaHPO_4$) which latter is practically neutral in reaction (pH 7.1).

When the above-described experiment with calcium carbonate is repeated with pure dicalcium phosphate, the pH value of the solution drops rather quickly to 5.1 as soon as surplus amounts of CO_2 are introduced, and the pH value remains stable at this level. Complete buffering against CO_2, therefore, is established in this case almost 1 pH unit lower than with calcium carbonate.

Reason for Lower Buffering Level When Dicalcium Phosphate Is Involved. The reason for this phenomenon is the peculiarity of the phosphates to change readily from one salt into another as the pH value of the solution rises or falls. In fact, the different phosphate salts may exist side by side, and the ratio of one to the other, in which they are present, is governed by the pH. The equilibrium between the two salts which establishes itself—though only very slowly—may be expressed by the following equation:

$$\underset{\substack{\textit{dicalcium}\\ \textit{phosphate}}}{2CaHPO_4} + \underset{\substack{\textit{carbonic}\\ \textit{acid}}}{H_2CO_3} \rightleftharpoons \underset{\substack{\textit{monocalcium}\\ \textit{phosphate}}}{Ca(H_2PO_4)_2} + \underset{\substack{\textit{calcium}\\ \textit{bicarbonate}}}{Ca(HCO_3)_2}$$

The practical significance of this behavior is that, in the absence of other bases, for instance in a soil with very low calcium content, dicalcium phosphate would cause acidification to pH 5.1, a pH level which is too low for the successful cultivation of many crop plants. Fortunately, the average cultivated soil does contain sufficient calcium to maintain the pH level above 6, and, if this should not be the case and acidification is observed, it can easily be corrected through liming.

Action of Tricalcium Phosphate. The third phosphoric acid salt, tricalcium phosphate [$Ca_3(PO_4)_2$], has, when pure, a pH value of 6.8 and behaves rather similarly to the diphosphate. It may be stated once more, however, that all of these measurements were taken at normal atmospheric pressure and at a temperature of 25°C.

When surplus amounts of CO_2 are introduced into an aqueous suspension of pure tricalcium phosphate, the pH value drops gradually until it becomes stable at pH 5.5. The reactions which result and which are responsible for this particular pH level are somewhat more complex than those described for the two other phosphoric acid salts and will not be explained here.

Natural Phosphate Rock. Natural phosphate rock, which contains mainly tricalcium phosphate, reacts in a manner very similar to what has just been outlined. Experiments with standard samples of Tennessee brown rock and Florida land pebble, obtained from the Bureau of Standards, Washington, D.C., gave the results shown in Table 15.1.

TABLE 15.1

Phosphate rock	P_2O_5	CaO	Fluorine	SiO_2	Original pH	pH after saturation with CO_2
Tennessee	31.55	44.06	3.4	10.1	6.52	4.65
Florida	35.33	49.62	3.76	7.4	6.72	4.72

The original pH value of the phosphate rock, as can be seen, was very close to neutral but dropped after saturation with carbon dioxide to the constant level of pH 4.7. The reason why buffering in this case is confined to a lower pH level than with pure tricalcium phosphate may be traced to certain impurities present in the rock, such as the fluorides and possible iron or aluminum salts. Such strong acidification, however, does not take place in the presence of calcium and need not be feared in normal field culture.

Buffering Action of Humic Acid and Its Salts

An aqueous solution of very pure humic acid prepared from peat has a pH value of 4. or 4.1 and acts as a buffer toward bases or strong acids in the same manner as was outlined for unbuffered and buffered acetic acid. Of greatest interest, however, are the water-insoluble salts which humic acid forms with various cations, in particular with calcium, magnesium, aluminum, manganese, and others. Most of these salts have a near neutral or somewhat alkaline reaction—between pH 5.8 and 7.5—but the most common of them, as well as the one most important for soil buffering, calcium humate, has, when pure (absolutely free of other cations), a pH value of approximately 9.

Action of Calcium Humate. When surplus amounts of carbon dioxide are introduced into an aqueous suspension of pure calcium humate, the pH value gradually drops to 4.7, at which point it remains stable no matter how much more carbon dioxide is added. This permanent buffering against carbon dioxide also results from the formation of calcium bicarbonate. The cause of the rather low pH level (as was shown, calcium bicarbonate has a pH value of 5.9) is the equilibrium which establishes itself between calcium bicarbonate and calcium humate in a fashion very similar to that described for calcium diphosphate and monophosphate.

Also otherwise, the conditions are very similar to those created by the phosphoric acid salts, and the unfavorably low pH value, which the buffering of calcium humate would permit, is not reached because such a high concentration of carbon dioxide as this would require does not occur in nature. The common presence of other humates with a pH above 5.8 offers additional resistance to the lowering of the pH to 4.7. In fact, the other water-insoluble humates have their own points of permanent buffering caused by the formation of carbonates.

Water-Soluble Humates Potentially Dangerous. The water-soluble humates which humic acid forms with sodium and potassium do not participate in the above-described process. These humates are easily leached out of the soil, which results not only in loss of valuable colloid humus but, at the same time, lowers or may even destroy the buffering action of the soil. Soil aggregation, on which colloid humus has a vital influence (see page 120), is likewise inhibited when colloid humus is lost. This accounts for the danger inherent in the application of overlarge amounts of fertilizers which contain the above-mentioned cations. Only previous soil analysis can prevent damage from this cause, which may be quite serious.

Buffering Action of Inorganic Colloids

The manner in which inorganic colloids, especially clay colloids, become saturated with calcium and how they react when they do become so charged has been explained in considerable detail in Chapter 11. It is evident that such inorganic colloids must likewise exert a buffering action in quite the same manner as has been described for the various calcium salts, especially calcium humate. There is no doubt that they do act in this fashion, though they are not quite as effective as calcium humate. Their buffering power is destroyed through the addition of surplus amounts of sodium or potassium salts which replace the calcium on the colloids in forcible base exchange. (See page 74).

PRACTICAL CONCLUSIONS

The practical conclusions to be drawn from this discussion of the mechanics of soil buffering are that calcium carbonate (limestone) as well as organic matter (as the source of carbon dioxide) are required to stabilize the soil against overacidification. Both of these substances must be present together; neither, by itself, can perform this important function. Superphosphate or phosphate rock will also serve, provided again that the soil is sufficiently rich in organic matter. Peat moss alone, especially acid peat moss, cannot produce buffering either, and powdered limestone (calcium carbonate) must be added at the same time. As was explained, it is not the humic acid but its calcium salt, calcium humate, which produces effective buffering. Further information on the importance of peat moss as an addition to soils lacking in humus will be found in Part VII (page 399).

16. SOIL PROFILES AND SOIL CLASSIFICATION

INFLUENCE OF CLIMATE ON SOIL FORMATION AND DEVELOPMENT

It will be remembered from the preceding chapters that water is intimately involved in the manifestations of many or most of the dynamic forces—physical, chemical, and biological—the presence or absence of water or the amount present often being decisive for the reactions which take place. The temperature likewise exerts a vital influence, a rise in temperature producing a proportionate intensification of many important dynamic processes. It has been estimated, for instance, that for every rise of temperature by 10°C (or 18° on the Fahrenheit scale) the speed of certain chemical reactions—especially of hydrolysis, carbonation, and oxidation—which are proceeding in the soil is approximately doubled, while the development of microorganisms is accelerated in approximately the same proportion.

This means that, under different sets of climatic conditions, the manner in which rocks weather as well as the kind of soil which results eventually will vary accordingly. In arid or boreal regions, where the temperature varies sharply from day to night or from summer to winter, chemical reactions are comparatively slow, because either water is lacking or the temperature is too low. In consequence, rocks crumble into gravel, and the resulting soil material will always be rather coarse. In humid tropical or subtropical regions, on the other hand, where the climate is more evenly warm and rainfall is plentiful, much finer-textured soils will result, and the formation of clayey soils will be common.

SOIL HORIZONS AND SOIL PROFILES

Formation of Soil Horizons

For these very same reasons, it must be expected that increasing depth from the surface will make a noticeable difference in the effectiveness of the various dynamic forces and in the manner in which their actions influence the development of the soil. The uppermost part of the soil, the so-called topsoil, being in immediate contact with the air, has free access to oxygen which is required for various types of chemical and biological reactions. Besides, it is directly exposed to insolation as well as to wind, and, in consequence, it is, more than any other part of the soil, subject to frequent changes in temperature. During summer topsoil will be warmer and during winter colder than lower soil layers. In addition, raw organic matter is, of course, largely concentrated in the topsoil, which results in a rich microbial life and, therewith, in the abundant production of carbon dioxide. The chemical reactions, which occur deeper down in the soil where the various inorganic and organic compounds—carried there by the drainage water—react with each other as well as with the minerals already present, must, by necessity, be quite different from those on the surface.

This change of conditions with increasing depth from the surface frequently results in the development of rather clearly distinguishable layers which differ in color, texture, and composition, and which are generally called *soil horizons.* A vertical cut through the soil down to the underlying rock, showing the sequence of horizons, is called a *soil profile.*

Importance of Lower Soil Horizons

The topsoil, being richest in readily available nutrients, is of greatest interest to the farmer and gardener. Because of its humus content, the topsoil is usually of somewhat darker color than the lower horizons—a feature which renders it readily distinguishable—and it will always be very much worth while to establish the topsoil depth before taking a virgin piece of land into cultivation. The lower horizons must not be overlooked, however, since on them depends not only the highly important drainage but also the ultimate fertility of the soil as such. If the lower horizons do not contain the nutrient reserves, which must be present to fit a soil for long-term cultivation, the topsoil is likely to wear out rather quickly. The history of American agriculture is full of instances where forest land was cleared for farming, which from its rich topsoil at first produced excellent crops but, because of its poor sandy subsoil, was reduced to worthlessness in less than 10 years.[1]

Factors Influencing Soil Modification

The differentiation of soils evidently commences with the composition of the original mixture of substances, which latter depends largely on

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[1] See, for instance, Hedrick, U. P., "The Land of the Crooked Tree," Oxford Univ. Press, New York, 1948.

chance deposition by water and wind. (See page 137.) The rock on which the soil rests—though it is likely to influence soil reaction and behavior and may contribute to its content—need not be responsible for the composition of the soil, and the term *parent material,* which is frequently applied to it, may be completely unjustified.

What type of soil horizons, if any, develop within the original mixture depends on the concerted influence of various factors, such as the type of plant cover which takes over and the climatic conditions which prevail. The height of the water table, the amount and the seasonal distribution of rainfall, the mean as well as the maximum and minimum summer and winter temperatures, and the presence or absence or abundance of snowfall all play their part in modifying the soil.

TERMS USED TO DESIGNATE SOIL TYPES

The changes produced in soil by a varying combination of these factors have been epitomized by soil scientists in technical terms, and, since some of these terms recur quite frequently in soil literature, they are explained here.

Melanization

Melanization (from the Greek *melanos*—black) refers to the incorporation of humus which imparts a darker color to the soil.

Podsolization

Podsolization (see page 184) refers to the characteristic development of a soil which has been exposed to excessive leaching with water, percolating through a top layer of raw humus and draining away into the subsoil.

Gleization

Gleization refers to the influence of a fluctuating water table. "Gley" is the enriched bluish or greenish waterlogged subhorizon, frequently found under peat or muck, which results when iron, calcium, aluminum, and magnesium are leached out of the upper layers. It consists mainly of mineral colloids and may be quite rich also in nitrate and potassium. It contains next to no humus, however, and is a biologically dead soil.

Laterization

Laterization (see page 186) refers to the influence of a special type of soil leaching which is confined to humid tropical climates.

SOIL CLASSIFICATION AND MAPPING

Since soils of different origin, or soils which are in a different state of development, cannot be expected to give identical results in plant culture and must, for best yields, be treated each according to its individual requirements, it is distinctly worth while to be aware of the distribution and location of the different soil types. For this reason, soil scientists have classified soils into systems which are based either on origin and state of development or on relationship, according to the dynamic conditions responsible for their formation. Such systems of classification apply distinguishing names to the different soil types—in the American systems these names usually derive from the locations where these types were first observed—and this makes it possible to plat the distribution of soils on special soil maps.

The science of soil classification and mapping is still rather young and, in consequence, is by no means entirely stabilized as yet. There is danger that the establishment of too many sub-sections will lead to hair splitting, and practical purposes might be served better by placing greater emphasis on the main soil types. One fact, which not infrequently leads the soil systematist *ad absurdum,* is that soils of very different origin may, under the influence of similar climatic conditions, develop in such a manner that they become nearly identical and can hardly be distinguished. If origin or "parent material" is taken as a basis for the establishment of a soil system, this may result in the classification of two soils which, for practical purposes, are identical in two different and separate sections. On the other hand, soil of essentially the same origin may, under the influence of local climatic conditions, such as variation in water table, develop in several different directions, and one may find in the same district and side by side three or more soils which, under cultivation, behave very differently, yet are intimately related in origin. All this is very bewildering for the uninitiated.

Usefulness and Limitations of Soil Maps

The proper interpretation of presently existing soil maps undoubtedly still requires specialized knowledge. On the other hand, they are of unquestioned value also to the practical farmer who has no training in soil science. Such maps do permit a preliminary appraisal of a locality as to its suitability for certain types of plant culture, and general hints concerning the kind of management a piece of land is likely to require may also be deduced. Besides, the soil map serves to call attention to the presence of different soil types, which should be kept separate in soil analysis, and which may require different treatment. The details, however, which the farmer or gardener needs to know for practical success must not be expected to be supplied by a soil map. As yet, there is no short cut which can take the place of personal experience and constant close observation, and soil analysis will be found essential for the needed intimate knowledge of the year-by-year requirements of a given soil.

No attempt will be made here to explain the various soil classification systems in further detail, since this would lead us too far astray from the purpose of this book. It may be worth while, however, to describe at least a few particularly characteristic soil types with rather distinct profile development.

CHARACTERISTIC SOIL TYPES

Podsol

Podsol (from the Russian word *zola*—ash, because of the characteristic gray color which develops directly below the topsoil), like a number of other important soil types, was first described by Russian soil scientists, hence its generally accepted name of Russian origin.

Its main feature, decisive for the development of the soil profile, is a cover of raw humus, producing an abundance of various organic acids such as humic acid, carbonic acid, and others. These acids, in moving downward with the drainage water, accelerate the decomposition of the silicates (see page 159) and leach the cations, such as iron, potassium, calcium, and magnesium, out of the upper horizons. (See page 239 for the development of hardpan or of bog iron ore which may result.) Naturally, a raw humus cover of sufficient thickness can develop only in dense forest, especially in coniferous or mixed forest, as well as under climatic conditions which favor humus accumulation. Podsols or podsolic soils, therefore, occur commonly in zones of northern to temperate regions which are—or were formerly—covered by dense forests.

The fact that this condition results in an impoverishment of the upper soil horizons does not, by necessity, create any hardship for the forest trees, since in most instances their roots can penetrate to sufficient depth to reach the enriched lower horizons where all the required nutrients are present. In fact, the continual leaching from the surface downward may actually serve to assure them of a steady supply.

Quite different is the situation if such soils are cleared of forest and are taken under cultivation. The surface humus, if not steadily replenished, will decompose and disappear quickly, and the impoverished upper soil horizons will require continual and ample applications of fertilizers.

Chernozem

Chernozem (also spelled Tshernosem—a Russian word, meaning black soil) results from a long-term coverage with a flora consisting mainly of grasses and is typical of the Russian steppe as well as of the American Great Plains. The climatic conditions which promote its formation are hot summers and cold winters, with moderate precipitation so that no excessive leaching occurs. The water table usually is so low that it has no, or next to no, influence.

Chernozems are essentially clay soils, rich in calcium but always near neutral in reaction. Very little raw humus is present on the surface, and humus in colloid form (a colloid humus content of 6 to 10 per cent or more is common) is distributed quite evenly throughout the soil, giving it its characteristic black color. The soil profile usually does not show any clearly developed horizons.

Such black soils are normally rich in available plant nutrients, especially potassium (as K_2O) and nitrogen, and they lend themselves readily to cultivation, especially where irrigation can be practiced. Regular applications of phosphate fertilizer may be required. Cultivation should, furthermore, take into account the fact that chernozems are highly subject to wind erosion, as the experiences in the dust bowls of Oklahoma, Kansas, Texas, and Colorado have demonstrated.

Prevention of Wind Erosion. This inherent danger can be neutralized, at least to a certain extent, through a suitable crop sequence which provides a continuous soil cover throughout the usually most critical fall and early winter period. A mulch and stubble cover, left on the field after harvest and through which the seeds are planted in spring without previous plowing, also may offer a solution.[2] Hedgerows, planted at right angles to the prevailing wind direction and approximately 400 ft apart, reduce not only the removal of soil by wind but also cut down evaporation and carbon dioxide dispersal. This results in substantial yield in-

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[2] Strom, John, "This May Revolutionize the Way You Grow Corn," *Country Gentleman* (February, 1952).

creases. (Increases of as much as 25 per cent have been reported.) Windbreak plantings of trees at a proportionately greater distance from each other serve equally well.

Rendzina

Another foreign soil term which is rather frequently mentioned is *rendzina.* This word is of Polish origin, though its derivation remains doubtful. Presumably, it refers to the sound produced when such soils are plowed.

Rendzina soils develop from more or less fine-textured calcareous soils under forest cover. The basic description "fine-textured, calcareous" is similar to that of chernozem soils with which rendzinas are frequently compared.

Physically, rendzinas are characterized by containing coarse debris, such as gravel and sand, in the humiferous upper horizon, comparatively little silt and clay being present. Chernozems usually are formed from loess—originally wind-deposited soil material—which does not contain coarse particles. Morphologically, rendzinas are distinguished by a humus-carrying near-neutral surface horizon which usually is clearly marked off from the greyish or whitish subsoil. In chernozems the humus is distributed evenly to a considerable depth.

Rendzina soils usually occur in limited areas between larger neighboring soil zones from which they differ owing to the strong influence of local conditions, such as parent material. They have even been called *intrazonal chernozem formations.*[3] The rather appropriate term ***humus-carbonate soils*** also has been applied to them.

They are able to support good forest growth of calcium-loving tree species, such as certain oaks, as well as good pasture. For agricultural purposes they are generally less suitable, being often rather low in nutrient content. In addition, they are likely to suffer from drought, once the forest cover is removed, owing to the rapidly draining subsoil. Some of the rendzinas, however, are excellent soils.

Laterite

The term Laterite comes from the Latin *later*—brick, because such soils generally are suitable for brick manufacture. The climatic conditions responsible for the formation of this group of soils consist of abundant rainfall, alternating with dry periods, and a persistently high temperature. This results in excessive leaching, extending to great depth.

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[3] Stebutt, A., Lehrbuch der allgemeinen Bodenkunde Borntraeger, Berlin (1930).

Organic soil matter decomposes very rapidly under such conditions, and the carbon dioxide, which thus is abundantly produced, acts to dissolve and to leach out the sodium and potassium. It is characteristic for lateritic soils that, in the decomposition of the silicates, the silica fraction (SiO_2) is almost entirely and sometimes completely leached out in colloidal form, and aluminum and iron remain behind as oxides (sesquioxides). The red color of most lateritic soils, so characteristic in parts of Mexico and South America, the Caribbean Islands, parts of South Africa, the Mediterranean region, and elsewhere, is caused by their iron content (Fe_2O_3).

With sufficient fertilization and proper tillage, lateritic soils, which usually drain readily and show good aggregation, are well suited for cultivation and produce excellent crops of rubber, coffee, bananas, pineapples, sugar cane, etc. They may also support mighty primeval forests.

17. CROP ROTATION

A book on soils cannot include details on farming practices, methods of plant culture, choice of crops, or erosion control. Besides, excellent and voluminous literature on all of these subjects is freely available. It seems desirable, however, to give at least a general outline of the meaning and purpose of crop rotation, since its advantages actually accrue from its beneficial influence on soil dynamic processes.

Continuous culture of one and the same crop, year after year, on the same piece of land is possible and—in spite of all claims to the contrary—may even be carried on for a very long time (as demonstrated, for instance, at Rothamsted). There is no doubt, however, that such a one-crop culture exposes the soil to numerous and serious dangers, besides being comparatively expensive if it is to result in high yields. Especially in regions of low rainfall and high winds or on sloping ground, it invites erosion and the accompanying loss of irreplaceable topsoil. Without careful control of the soil nutrient balance—regular replacement of organic matter and annual application of appropriate fertilizer—continuous one-crop culture is bound to result eventually in complete impoverishment and ruin of the soil through one-sided usage.

Soil Used Merely as Support

To be sure, it is possible, especially with artificial irrigation, to consider the soil merely as a growing medium—like the gravel in hydroponics—to which all nutrients are applied as required, but this is a pretty expensive proposition and, therefore, uneconomical for the average field crop.[1] For the large-scale culture of grains and other quan-

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[1] Rose culture in Texas rather closely approximates such a procedure, since the fields are located on natural deposits of a very fine white sand which has a very low natural nutrient content. The application of fairly high amounts of artificial fertilizer, therefore, is indispensable. Each field is occupied by roses for no more than 2 years in succession and then is allowed to recover for 4 years, during which time legumes usually are grown or weeds simply are allowed to take over. The latter are plowed under before roses are returned to the same piece of land. The

tity crops—most important for the world's economy—such a system would probably present insurmountable technical difficulties, and it is indeed highly doubtful whether the huge amounts of organic and inorganic fertilizers which it would require could be made available at all. Since agriculture, in order to be worth the effort, must result in a profit, and since the profit depends on the cost of production, the sensible thing to do is to hold production costs down to a minimum.

Dynamic Soil Properties Used to Advantage

If, instead of using the soil as a dead growing medium, its dynamic properties are taken into account and are given the fullest possible chance to exert their influence through well-considered usage, soil fertility can be maintained and even increased at minimum cost. If crops are changed judiciously and follow each other in the most advantageous sequence, manure or compost and artificial fertilizers need not be employed every year and can be applied in minimum amounts to the crops which utilize them most efficiently.

Advantages of Legumes

The difference is made up by including a leguminous crop, such as alfalfa, in the rotation, which adds both nitrogen and organic matter to the soil when it is plowed under. The latter is particularly important, because humus decomposition is accelerated in continually plowed soil, causing it to be used up rapidly. Another beneficial effect of the inclusion of deep-rooted legumes, such as alfalfa or clover, in a rotation consists in the utilization of soil nutrients from lower soil levels, which are transported up to leaves and stems and, at their decay (after plowing), are added to the upper soil layers. The fact that the deep roots of the legumes, at their decay, contribute to the physical improvement of the soil by loosening it must not be overlooked either.

Other Advantages of Crop Rotation

Well-planned crop rotation, by keeping the soil more or less continuously occupied, is an excellent means of checking erosion or soil loss.

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main advantages of the fine sand and the reasons why it was chosen are its natural pH value of 6.5 and its propensity for conserving moisture as well as for holding it readily available. The latter factor, in particular, is of extreme importance under the prevailing circumstances, since artificial irrigation is impossible, and natural precipitation in this part of the country is normally high in early spring but nearly absent during the summer months.

That plant diseases are more readily controlled when crops are changed from year to year is evident from the fact that most plant parasites which are able to winter over in the soil are limited to one particular type of host plant. If this plant is not returned to the same plot of ground for 4 or 5 years, the parasitic organisms have much less of a chance to become a serious menace.

Sequence in Crop Rotation

It is obvious that crop rotation offers numerous and important advantages, but it becomes most clearly apparent that dynamic processes are responsible when one considers that different sequences in rotation produce entirely different results.

What kind of rotation is most advantageous depends, of course, on circumstances, most of all on the climate, including the soil conditions, but also on the type of the main cash crop. This cannot be discussed here. The importance, however, of the proper sequence of crops in a rotation may be demonstrated by one example. In a rotation including sugar beets, potatoes, and 2 or more years of a legume crop such as alfalfa, it was found that sugar beets, when following alfalfa, gave low yields, but when 1 year removed from the alfalfa crop—when potatoes were planted the first year after the alfalfa and sugar beets the second year—both potatoes and sugar beets gave high yields. Potatoes, when planted the second year after the alfalfa was plowed under, gave lower yields than when planted directly after alfalfa. The most advantageous sequence in this particular type of rotation, therefore, would be: alfalfa, potatoes, sugar beets. It must be assumed that the nutritive requirements of the potatoes are quite different from those of the sugar beets, and that the interaction of the metabolic processes of the potatoes with the soil dynamic processes—for instance the decay of the alfalfa remains—serves to produce particularly favorable conditions for the development of the sugar beets.

These strange mutual influences are as yet by no means completely understood, but a considerable and ever-increasing amount of data on favorable crop sequences, which were obtained experimentally, do exist and are available for the guidance of the farmer.

The natural laws which govern soil fertility, as well as the various methods of treatment which may be employed to maintain or to improve soil fertility, are discussed in Parts VI and VII.

PART IV

The Main Nutrient Elements, Their Origin and Their Behavior in the Soil

INTRODUCTION

To consider some of the most important nutrient elements separately, as has been done in the following chapters, will serve to bring soil dynamic processes into sharper focus. It was decided to include in these chapters the origin of the elements as well as the manner in which their most common compounds are formed in nature, in order to provide a source of ready reference. Conclusions were drawn for practical application.

The following chapters, therefore, are intermediate between Parts III and V and should be read in this order. Each of the elements described has its individual peculiarities; their "cycles" do not coincide, nor are they governed by the same factors. Comprehension of their individual behavior will make their combined action more readily understandable. Knowledge of the origin of the natural supplies of these nutritive elements and of the manner in which some of them are prepared in the form of compounds for fertilizer should assist in reducing guesswork in artificial supplementation.

18. THE STORY OF NITROGEN

MINERAL COMPOUNDS OF NITROGEN IN NATURE

Elemental nitrogen is the main constituent of the air (approximately 79 per cent by volume), and, in consequence, one might expect that deposits of mineral compounds of nitrogen would be correspondingly common on the surface of the earth. Actually, this is not the case. Though various nitrogen compounds (organic and inorganic) are generally present in the soil in scattered amounts, fair-sized deposits of any one particular mineral compound of nitrogen are quite rare and occur only locally in strictly delimited and always at least semiarid regions. The main reason for this phenomenon is the high water solubility of these salts, which renders them very susceptible to leaching, and which prevents their accumulation except where the annual rainfall is very low. The fact that true mineral soils as a rule have a very low nitrogen content must be traced to the same cause.

Chile Saltpeter, Potassium Nitrate, and Ammonium Sulfate

The so-called Chile saltpeter [sodium nitrate ($NaNO_3$)] is one of the few naturally occurring nitrogen salts of real importance. It exists in extensive, commercially exploited deposits in northern Chile as well as in the neighboring parts of Peru and Bolivia. Deposits are known also in southern California and Nevada. Potassium nitrate [niter (KNO_3)] occurs naturally in Spain, Egypt, Persia, and India. (See Chapter 20.) Ammonium sulfate [$(NH_4)_2SO_4$] is found as a natural deposit in volcanic regions, usually as a double salt with magnesium, such as boussingaultite [$(NH_4)_2SO_4 \cdot MgSO_46H_2O$]. The latter is mined, for instance, at the fumaroles of Montecerboli in Tuscany, Italy. Most of the ammonium sulfate used for fertilizer purposes, however, is obtained as a by-product in the manufacture of coke and coal gas. (See page 299.)

A rather small amount of the elemental atmospheric nitrogen (approximately 5 to 6 lb/acre/year at an average) is added to the soil during thunderstorms. In this process, discharges of atmospheric electricity produce nitrous oxide, which rain carries into the soil as nitric acid, where it is quickly converted into nitrates. Normal rain as well as snow carry a small amount of nitrous oxide also. Much more significant are the amounts of atmospheric nitrogen which are regularly incorporated in the soil through the activities of nitrogen-fixing bacteria. Further details on this important process will be given later in this chapter (page 200.)

THE NITROGEN CYCLE

From the foregoing it is evident that soil nitrogen, which is one of the most important plant nutrients, occupies a rather singular position, very different from phosphorus and potassium which are always present in the soil in mineral form. Where does the soil nitrogen originate?

Origin of Soil Nitrogen

It must be assumed that the initial amounts of nitrogen were provided by certain soil bacteria which, being able to absorb and fix atmospheric nitrogen, made it available to higher plants. These amounts, though, are always relatively small, and bacteria could not possibly be expected to supply all that is needed, if the nitrogen which they manage to accumulate would simply be withdrawn by higher plants and lost. Actually, it is not lost, and, once nitrogen has been fixed by bacteria, it enters on an eternal round. The plants which assimilate the nitrogen from the soil include it in their cell structure and, when these plants are eaten by animals (large or small), the nitrogen is incorporated in their body tissue or is discharged in excrements (manure). When plants (as compost or green manure) or animal bodies are buried and decompose, the nitrogen enters the soil once more. The cycle always proceeds from simple inorganic compounds to highly complex organic compounds, then through decomposition back to simple inorganic compounds and around again, without ceasing. The nitrogen-fixing bacteria then only have to take up the slack, so to speak, by supplying mainly those amounts of nitrogen which get lost during the various complex processes forming the chain. Some of the nitrogen always does get lost to the air.[1] No doubt the

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[1] According to recent findings [Adel, A., *Science* (June 1, 1951)], nitrogen is released from decaying organic matter as nitrous oxide, in which form it is the most abundant constituent of the soil atmosphere. In the lower air layers above the soil surface, nitrous oxide likewise is very abundant, diminishing at higher altitudes. When diffusing into the upper atmosphere, it is decomposed photochemically into

nitrogen-fixing bacteria are a very important link in this chain, since without them even uncultivated soil would unavoidably become gradually poorer and poorer in nitrogen.

The above condensed outline makes it plain that organic substances and the microorganisms which decompose and modify them control, to a large measure, the nitrogen economy of virgin soil. In consequence of this, soil nitrogen supplies are highly subject to influence through agricultural procedures, and the maintenance of a satisfactory nitrogen level in cultivated soils actually depends almost entirely upon proper soil treatment.

Ammonification; Decomposition of Organic Substances and Hydrolysis

Nitrogen is contained in the various organic substances mainly in the form of proteins. (See page 28). The breakdown of these highly complex compounds into simple inorganic compounds which plants can assimilate proceeds in a series of steps. In the beginning various lower animals, such as insects and worms, participate very actively, but most of the work of decomposition is performed by a large variety of fungi, actinomyces, and bacteria. The most important chemical process involved is biological hydrolysis which results in a gradual breakdown of the proteins into albuminoses, peptones, amino acids, and finally ammonia, mainly through the interaction of proteolytic (protein-decomposing) enzymes, produced by the various microorganisms. The whole chain of processes, culminating in the production of ammonia, is generally designated as ammonification.

Nitrification; Oxidation of Ammonia

The reactions to which soil nitrogen is subject do not end, however, with the production of ammonia or of ammonium salts (such as ammonium carbonate), since two distinct groups of bacteria are continually active in oxidizing ammonium salts into nitrites and nitrates, by which process they obtain the energy required for their development. These processes are generally designated as "nitrification."

The following equations express the basic conversion, though calcium —or some other base such as potassium or magnesium—usually enters simultaneously into an association with the acids which are evolved, and various intermediate steps which are always included in biological

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nitrogen, oxygen, and nitrous oxide. Nitrous oxide also is decomposed photochemically into nitrogen and oxygen. Presumably, nitrous oxide accumulates above the earth's surface until the rates of accumulation and decomposition are equal. Nitrous oxide, therefore, appears to be an important phase in the nitrogen cycle.

processes render the whole conversion actually much less simple than it is shown here.

First step:

$$\underset{\textit{ammonia}}{2NH_4} + \underset{\textit{oxygen}}{3O_2} = \underset{\textit{nitrous acid}}{2HNO_2} + \underset{\textit{water}}{2H_2O}$$

This is accomplished by the bacteria *Nitrosomonas* and *Nitrosococcus*.

Second step:

$$\underset{\textit{nitrous acid}}{2HNO_2} + \underset{\textit{oxygen}}{O_2} = \underset{\textit{nitric acid}}{2HNO_3}$$

This is accomplished by bacteria which are grouped together under the name *Nitrobacter*.

Nitrite and Nitrate. The salts of nitrous acid are nitrites, and those of nitric acid are nitrates. Nitrites, however, are very unstable in the presence of oxygen, and under normal conditions the two steps of conversion follow each other so closely that an actual accumulation of nitrites in the soil is extremely rare. In consequence, the development of nitrite toxicity—nitrites in concentration are toxic to higher plants—need not be feared under normal conditions.

PREFERENCES OF PLANTS FOR DIFFERENT FORMS OF NITROGEN

Both ammonium and nitrate are absorbed by higher plants, and certain plants even appear to have a definite preference for nitrogen in ammonium form. The latter include certain forest trees, such as American beech, red maple, and most Ericaceae such as rhododendron. Certain important crop plants, for instance, potatoes and oats, also appear to prefer nitrogen in the form of ammonium. Rice as well as various other lowland grasses likewise belong in this category, and many conifers, probably because of their symbiosis with mycorhizal fungi, may actually be harmed by nitrate applications. In general, however, it is nitrate which must be considered as the most important source of nitrogen for higher plants, and it even appears that certain plants which are known to utilize ammonium directly can do so only when a certain proportional amount of nitrate is present at the same time.

DEVELOPMENT OF AMMONIFYING AND NITRIFYING MICROORGANISMS

Since the various microorganisms are indispensable for assuring a steady supply of available soil nitrogen, cultural methods must be adjusted so as to produce favorable conditions for the development of these microorganisms. It is important, therefore, to understand clearly what these conditions are.

Water

Ammonification, which, as pointed out, is a hydrolytic process (page 156), requires the presence of sufficient amounts of water. (See also page 112.) On the other hand, all the most important microorganisms involved in this chain of processes are aerobic, which means that they require oxygen. One of the most important by-products of ammonification is carbon dioxide, which is produced in large amounts, and which can be evolved only when oxygen is freely available. In consequence, a very high water content is undesirable because it excludes the required oxygen. Drainage, therefore, will be an aid in soils which are inclined to remain too wet. Very dry conditions, on the other hand, are equally inhibitive, since a certain amount of water is required. The maximum of favorable water content is approximately 50 per cent of saturation, or, in other words, about half as much water as the soil would be able to hold when saturated. More than that will exclude too much of the needed oxygen, and less than 20 per cent will slow down hydrolysis. This applies to both ammonification and nitrification.

Temperature

The temperature likewise is of importance, since activity of most of the microorganisms involved stops slightly above the freezing point. Nitrification commences slowly at 45° or 50°F and reaches an optimum between 75° and 95°F (25° to 35°C). It is for this reason that spring applications of nitrate fertilizers are so effective, since they assist in bridging the gap until the temperature rises sufficiently for the natural development of nitrate. For the opposite reason—a rather even temperature above 60°F or even above 70°F—greenhouse soils are said to develop occasionally an undesirably high accumulation of nitrites. This is not likely to happen when organic matter is the only source of nitrate formation, since under such conditions a natural balance between the ammonifying and the nitrifying bacteria appears to establish itself. It can and does occur, however, when, besides manure, ammonium salts and, perhaps, nitrate also, have been incorporated in the soil.[2]

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[2] The same danger exists when manure as well as a nitrogen-rich fertilizer are added to the compost pile, producing an abnormally high ammonium content in the resulting compost soil. When such a compost soil is steam sterilized, nitrite toxicity is almost sure to result.

Feeding the Microorganisms

Since the microorganisms require for their life processes additional nutrient elements, in particular phosphorus but also potassium, magnesium, and calcium, the application of such fertilizers in readily available form definitely assists in speeding up both ammonification and nitrification. Calcium and magnesium, which may be applied together in the form of ground magnesium containing limestone (dolomite), have the additional beneficial effect of neutralizing the various acids which the bacteria develop and which, if they were allowed to accumulate, would actually inhibit their own further development. It may be mentioned in this connection that, contrary to common belief, soil microorganisms are capable of withstanding fairly high salt concentrations—more so than higher plants—so that injury of the microorganisms through application of fertilizer salts is not to be feared.

The influence of soil pH values on the ammonifying and nitrifying bacteria has been treated in Part II. (See page 112.)

THE CARBON-NITROGEN RATIO

The previously mentioned fact that the microorganisms themselves utilize ammonium salts and nitrates in the building of their own bodies is significant. This results in the temporary withdrawal of considerable amounts of these readily available forms of nitrogen and in converting them once more into complex organic compounds. Since microorganisms are very short lived and decompose readily when dead, the result of this process under average conditions is actually the creation of a rather valuable nitrogen reserve. Occasionally this competition with higher plants, however, may become distinctly detrimental to the latter; a condition which is most pronounced when large quantities of undecomposed organic matter—especially such as strawy manure, straw, and sawdust—are added to the soil.

Effects of Plowing Under Organic Materials Rich in Cellulose

The reason for this phenomenon is that organic substances of this type are much richer in carbohydrates (such as cellulose and hemicellulose) and, therewith, in carbon, than in proteins which contain nitrogen. The microorganisms, which effect the decomposition, use carbon compounds as a source of energy, and the presence of large amounts of such substances causes them to increase very rapidly. Their luxurious development naturally requires also fairly large amounts of nitrogen which—not being present in sufficient amounts in the decomposing matter—is largely withdrawn from the soil, causing temporary nitrogen impoverishment.

In consequence, immediately after organic matter which has a high content of cellulose (carbohydrate) has been incorporated in the soil, harmful effects are likely to be observed on higher plants, but 6 to 12 months later beneficial results will become evident. In the interest of greatest efficiency one should, therefore, either compost strawy organic materials before adding them to the soil or add them to the soil 8 to 9 months before plants are set out or seeds are sown. The application of nitrogen fertilizer will not only speed up the decomposition of strawy materials but will at the same time minimize the effect of the temporary deficiency which will result from their incorporation.

The plowing under of "green manure"—such as buckwheat or rye—can have very much the same effect, especially if plowing is delayed until the green-manure crop is near maturity. (See page 257.) This explains why it is a serious error to sow rye grass and to mow it a few times before plowing it under when a lawn is to be established. Such a procedure actually robs the soil of available nitrogen, and one should instead sow several crops of rye grass, plowing it under whenever it reaches a height of 5 or 6 in., and applying nitrogen fertilizer—or still better a complete fertilizer—with every plowing.

Hay or any other type of dry plant material decomposes much more slowly than do fresh plants because of reduced water solubility of the various compounds contained in the tissues, resulting in higher resistance to microorganic activity.

Residues of leguminous plants, such as clover and alfalfa, cause, even when mature, less of a nitrogen depression, or at any rate a shorter depression, than does straw, because the tissues of leguminous plants are richer in proteins (nitrogen) in proportion to carbohydrates (carbon) than the residues of most other plants. In all the above cases, it is this proportion between carbon and nitrogen, the so-called carbon-nitrogen ratio, which matters. The wider the carbon-nitrogen ratio (the more carbon is present in proportion to nitrogen), the smaller is the amount of ammonia liberated.

LEGUMINOUS PLANTS

Leguminous plants are the only higher plants which grow well on soil to which raw organic matter, rich in cellulose, has been added. This is because the nodule-forming bacteria on their roots are able to fix atmospheric nitrogen, thus rendering these plants independent of soil nitrogen. As explained above, soil nitrogen is at a premium when substances rich in carbohydrates are decomposing. Actually, the highly significant symbiosis between various leguminous plants and bacteria is most efficient and results in greatest nitrogen gain in soils which have a low content of available nitrogen. If plenty of soil nitrogen is available, the leguminous plants will utilize it, and little or no nodule formation will take place. This is an extremely important fact, since the plowing under of leguminous plants under such conditions will result in no appreciable gain in soil nitrogen.

Importance of Plowing Under the Whole Plants

It is equally important to realize that as much as three quarters of the nitrogen (in protein form) which legumes accumulate with the help of their nodule-forming bacteria is likely to be stored in the tops of the plants, not in their roots. If the tops are cut for hay and only the roots are plowed under, there may actually be a slight loss of soil nitrogen. At best there is neither gain nor loss. In a rotation including alfalfa the last cut, at least, must be foregone, and the whole plants must be plowed under when the time comes to do so, or one of the main purposes of the leguminous crop will be defeated.

Feeding and Inoculation

It has been found that the addition of readily available calcium (gypsum or ground limestone, since these plants thrive best on a slightly acid soil) as well as of phosphorus and potassium, where the soil content of these substances was low, increased the gain in nitrogen very appreciably. Inoculation with the proper bacteria—especially for alfalfa and soybeans, if these had not previously been grown on the particular field—resulted in a further very substantial increase in nitrogen gain. Under favorable conditions and provided the whole crop is turned under, the average increase in soil nitrogen from a leguminous crop is estimated to amount to approximately 100 lb/acre, but under optimum conditions on seriously nitrogen-deficient soil, this may go as high as 400 lb/acre (in the form of organic compounds and eventually ammonia).

Excretion of Nitrogen by Legumes

The benefit derived by nonleguminous plants from association with a legume—such as oats with peas—on nitrogen-poor soils is now known to result from actual nitrogen excretion by the roots of the legume. Sloughed-off nodules and portions of the legume roots cannot account for the amount of nitrogen present in the soil. That root excretion is responsible was first demonstrated by Lipman,[3] who used a pure quartz sand treated with all necessary plant nutrients except nitrogen. He placed a smaller pot within a larger one, planting oats in the inner pot and peas in the outer one. The results were that as long as the inner pot was porous, allowing the passage of solutes, the oats developed normally and, on analysis, showed considerable quantities of nitrogen. When the inner pot was glazed, the oats grew poorly and contained little nitrogen. Other investigators who repeated this experiment obtained very similar results. The conclusion is that the mixed seeding of leguminous and nonleguminous plants on nitrogen-poor soils is to be highly recommended.

FREE-LIVING NITROGEN-FIXING BACTERIA

Besides the nodule-forming bacteria which live in symbiosis with leguminous plants, there are also several others, such as *Azotobacter*, which live free in the soil but which likewise are able to fix atmospheric nitrogen. From all investigations to date, however, it appears that their activity in cultivated soils is much less significant. The amount of nitrogen which they are likely to add to the soil is so small (approximately 10 lb/acre/year under average conditions at a pH between 6 and 8, though it may go as high as 20 or 25 lb/acre/year) that the practical value of this type of nitrogen fixation in cultivated soils remains doubtful. If it is assumed, as has been suggested, that the amount of nitrogen gained through fixation by free-living bacteria approximately equals the amount which is lost through denitrification and other types of volatilization of nitrogen, this would at least leave the slate clean for a gain by other means. The fact that the free-living nitrogen-fixing bacteria (just as do those which live in symbiosis with legumes) utilize soil nitrogen, if the latter is freely available, makes them appear even less important for cultivated soils, since under such conditions they may not fix any atmospheric nitrogen at all.

On the other hand, it must not be overlooked that *Azotobacter* and other free-living nitrogen fixers are present in all soils (the symbiotic fixers can live only where legumes grow) and that they are among the first organisms which develop in newly formed soils. Therefore, they

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[3] Lipman, J. G., *New Jersey Agri. Expt. Sta. Bull. No. 607* (1936). See also Waksman, S. A., "Soil Microbiology," pp. 224–226, New York, John Wiley & Sons, Inc., 1952.

undoubtedly must largely be credited with making raw mineral soils habitable for higher plants.[4]

NITROGEN LOSS

Through Leaching

Loss of soil nitrogen, outside of what is withdrawn by growing plants, is due primarily to leaching. Nitrates, in particular, are highly soluble in water and are very little adsorbed by the soil colloids. This renders them most susceptible to loss in drainage. Soil analysis before and after a heavy rain reveals an appreciable drop in soil nitrate content. Ammonium, on the other hand, is rather firmly adsorbed by the soil colloids and, in consequence, is only little exposed to leaching. Therefore, it represents a safe reserve from which the lost nitrate supply can be, and is, quickly replenished. If soil analysis is repeated about a week later, it will be found that nitrate content has returned to approximately the same level existing before the rain.

Through Denitrification

A further loss of soil nitrogen may result from the reduction of nitrate to nitrite and then to free nitrogen or ammonia which is caused by various bacteria (aerobic or anaerobic) under anaerobic conditions (when oxygen is lacking). These bacteria simply obtain the oxygen they need—in order to utilize carbon compounds as sources of energy—from the nitrate, which results in the reduction of the latter. (See reduction, page 161.) The elemental nitrogen is lost to the air. As is evident from the foregoing, this process, denitrification, is favored by lack of soil aeration which may be caused by high water content or by soil compaction. It is assisted, furthermore, by the abundant presence of undecayed organic matter which is rich in carbon, especially when large amounts of nitrates are present or added at the same time. Under normal or average conditions of good soil aeration, denitrification is generally considered insignificant and not of economic importance.

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[4] In soils too acid for *Azotobacter*, which does not thrive at a pH below 6 or much above 7.5, several species of the anaerobic genus *Clostridium* take over, though elsewhere *Clostridium* is likely to be present together with *Azotobacter*.

In soils of near neutral reaction the two types establish a sort of collaboration, *Azotobacter* assisting the anaerobic *Clostridium* by consuming the oxygen which limits its development, and *Clostridium* assisting *Azotobacter* by breaking down its waste products. (Waksman, S. A., "Soil Microbiology," pp. 193–200, New York, John Wiley & Sons, Inc., 1952.)

LOSS OF AMMONIA

The loss of ammonia from manure when lime—especially dehydrated lime—is added to it, is a purely chemical process. The ammonia is freed because it is dislodged by the aggressive calcium. This fact is so commonly known that the warning never to apply manure and lime together, because of the resulting terrific loss of valuable nitrogen, will hardly require repetition. It is still frequently overlooked, however, that the same deleterious effect results when hydrated lime (instead of the very slow-acting ground limestone) is added to compost, and this fact may, therefore, be emphasized here.

THE NITROGEN CYCLE UNDER NATURAL CONDITIONS

The nitrogen cycle, with all its ramifications, works efficiently only under natural conditions when the soil is continuously occupied by plants. The automatic return to the soil of all plant remains, as the upper parts of the plants die and fall, plus the activity of nitrogen-fixing bacteria, results even in a slow though steady gain in soil nitrogen. The nitrogen-rich prairie soils of North America developed in this manner through the course of centuries.

Low Nitrate Level of Virgin Soils

Curiously, the nitrate level in an undisturbed natural soil is usually quite low (5 to 15 lb/acre in spring and approximately twice as much in summer). Yet this low level is perfectly sufficient because the nitrate is replaced by the nitrifying bacteria as quickly as it is used. In fact, the rapid use of the available nitrate by the higher plants stimulates the production of nitrate. If conditions permit nitrate accumulation, production usually stops somewhere near the 100 lb/acre level, at which point the nitrifying bacteria appear to become inactive under natural conditions. A further check on overproduction is exercised by the supply of oxygen which the nitrifying bacteria require, and which under a thick cover of grasses and humus, is never available very freely. The consequence of these conditions is that hardly any leaching of nitrates takes place and that nitrogen accumulates in the form of ammonium and as a component of undecomposed organic matter. In fact, it is this condition alone which, in nature, makes the nitrogen cycle possible.

BREAKING THE NITROGEN CYCLE

As soon as a virgin soil, a rich prairie soil for instance, is put under cultivation and is plowed, the nitrogen cycle is radically affected, and the thorough aeration which results produces a change in the whole soil picture. Decomposition of the organic matter is greatly accelerated, the nitrifying bacteria become extremely active, and large amounts of the nitrates which are produced are lost through leaching because of increased drainage.[5] Since only parts of the average crop plants—roots and stubble—are returned to the soil, a further large amount of nitrogen (50 to 60 lb/acre/year) is lost from the soil in harvest. The nitrogen content of the soil then is bound to decrease rapidly from year to year.

MAINTAINING A SATISFACTORY NITROGEN LEVEL

A leguminous crop once in 4 years cannot keep up the nitrogen supply, since it is not likely to add more than 100 lb of nitrogen/acre at one time, even if plowed down in its entirety. Spread over 4 years, this would amount to no more than 25 lb/acre year, which is definitely insufficient.

Nor could manure or compost ever be expected to be available in the large amounts which would be required to maintain satisfactory nitrogen supplies in all the millions of acres of cultivated soil. This means that if a soil is cultivated intensively, and especially if crops which require much nitrogen are grown continuously, artificial nitrogen fertilizers must be used. Unfortunately, the amount of fertilizer which would be required to make up the whole balance, if no nitrogen conservation were practiced at all, would be so enormous (over 3 million tons/year for the United States alone) that it could never be supplied either.

The only procedure which will maintain a satisfactory nitrogen level without straining available resources is a combination of nitrogen conservation and judicious fertilizer application. Crop rotation, especially if it includes a legume crop which is plowed under, helps very materially

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[5] F. T. Shutt [*Can. Dept. Agri. Bull. No. 44* (1925)] reported that, on cultivating a virgin prairie soil, a loss of over 100 lb of nitrogen annually occurred for 22 years. Only one third of this loss was accounted for by the crop grown.

H. Jenny [*Missouri State Coll. Agr. Expt. Sta. Bull. No. 324* (1933)] calculated that, during cultivation of a virgin soil, 25 per cent of the soil nitrogen is lost during the first 20 years, 20 per cent during the second 20 years, and 7 per cent during the third 20 years.

to conserve nitrogen, and so-called ley farming—in which every field is turned into pasture for several years—gives the soil a chance to recover. All the farm manure and compost that can be produced should be applied, and nitrogen fertilizer, especially ammonium fertilizer, which is less subject to loss by leaching, need then serve only to make up the remaining deficit.

In conclusion it may once more be emphasized that, as far as nitrogen is concerned, there is a vital difference between undisturbed natural soil and cultivated soil. It should always be remembered that the nitrogen reserves which a virgin soil has accumulated over hundreds of years can be exhausted very quickly through cultivation, if no measures are taken to conserve and to replace them.

19. THE STORY OF PHOSPHORUS

Elemental phosphorus (P) does not occur in nature in a free state—its high capacity for oxidation makes this impossible—but the numerous compounds, especially phosphates, which it forms readily, are common components of many minerals.

APATITE

The parent substance and original source of all of the various phosphates occurring in nature is the mineral apatite, which may consist of as much as 96 per cent tricalcium phosphate. It also always contains fluorine and chlorine, usually in the double salt $CaF_2(Cl_2)$, as well as a certain amount of silicic acid. Iron and manganese are frequently present.

The crystals of apatite, usually clear and transparent though sometimes reddish-violet or green colored, may be large—several pounds in weight—but most commonly are microscopically small and needle shaped. It is this latter type which is present in most igneous as well as in many metamorphic rocks. Most types of granite and basalt as well as gneiss contain them, and, when such rocks decompose under the influence of weathering, the apatite and its component phosphate become incorporated in the soil. The fluorine content of the apatite is responsible for the presence of varying amounts of fluorine in all raw phosphates as well as in the superphosphate prepared from them. (See calcium fluoride, page 223, and fluorine in phosphate rock, page 305.)

In certain parts of the world—especially in Canada but also in Norway, Russia, and elsewhere—extensive separate deposits of apatite, believed to be of secondary origin, have been located. The Canadian apatite formerly was mined extensively for fertilizer purposes, but its solubility and, therewith, its phosphorus availability are extremely low, and for superphosphate production the so-called "phosphate rock" (phosphorite) is generally preferred. Norway appears to be, at present, the only country which employs apatite in the manufacture of superphosphate.

PHOSPHATE ROCK

The origin of phosphate rock offers a rather fascinating subject for study. Apparently, this material resulted from a chain of biological and chemical processes, the supposition being that large accumulations of animal remains were responsible for its formation. The frequent presence of still-recognizable bones and teeth of prehistoric animals lends strong support to this assumption. Such accumulations could develop either as marine deposits, later exposed when the sea receded, or could result inland, when catastrophic changes in the climate or other violent disturbances caused the death of large numbers of animals. Many different types of such catastrophes or cataclysms, including volcanic eruption, flood, fire, and ice, can readily be pictured as possible causes of mass death either in water or on dry land. Floods may have flushed the bodies together into one place. It must be assumed that, during the many thousands of years since these deposits were formed, the animal bodies disintegrated completely, leaving behind the phosphates which derived chiefly from the bones. (Raw bones contain approximately 22 per cent phosphoric acid.) Depending on the manner of its deposition, the leaching to which it undoubtedly was exposed, and the amount of impurities (such as clay or limestone) which were deposited at the same time, phosphate rock contains from 18 to 81 per cent tricalcium phosphate. Nitrogenous and other compounds, likewise derived from the decomposing animal bodies, are always present—commonly in the form of carbonates—but never in more than small amounts.

The well known Florida phosphate deposits are, by some writers, presumed to have originated through the decomposition of rocks rich in phosphoric acid. Though this is not impossible, it appears to be rather unlikely, especially since the general composition of the Florida phosphates is very similar to other types of phosphate rock. The Florida phosphates are typified by being contaminated with clay which must be washed out before processing. In Utah, Wyoming, and Montana, phosphate rock occurs in pockets or veins usually interbedded between limestones and shales. Some of these veins are 4 to 6 ft thick and extend for several miles. The Tennessee deposits are generally believed to be residual from the weathering of highly phosphatic limestones.

Most of the phosphate rock now in commerce in North America and largely employed in the manufacture of superphosphate comes from Florida and Tennessee. The other deposits mentioned above which, actually, are exceptionally rich, have hardly been touched as yet. The majority are located on government-owned land, representing a reserve held for future use. Similar deposits exist also in other parts of the world, such as North Africa, the Christmas and Gilbert islands, some of the Society islands, Russia, Belgium, and France.

GUANO

Guano and fish guano, or fish meal, which must be considered as sources of phosphorus (as P_2O_5) for fertilizer purposes, are treated in Chapter 26, pages 289-90.

BEHAVIOR OF PHOSPHATE COMPOUNDS IN THE SOIL

Since phosphate is an essential plant nutrient, a thorough understanding of the behavior of the various phosphate compounds in the soil is invaluable. Without it, proper soil treatment for optimum availability of phosphates to plants is not possible. The discussion following will answer, in particular, the three questions:

1. Which of the various phosphate compounds is the most important one for plant nutrition?
2. What dynamic soil processes influencing availability affect the various phosphates?
3. What influence has the soil pH on these processes?

Trivalent Phosphoric Acid

Phosphoric acid (H_3PO_4) is a trivalent acid, which means that the PO_4^{---} anion requires 3 hydrogen cations for electrical equilibrium. Any or all of the H^+ ions can be replaced in base exchange by other cations, resulting in the formation of salts.

Three Calcium Phosphates

For plant nutrition the calcium phosphates are of greatest importance and will, therefore, be considered first. These are formed when the hydrogen is replaced by calcium either partly or totally. Depending on whether 1, 2, or all 3 of the hydrogen ions are replaced by calcium ions, one of three different salts results, as follows:

Monocalcium phosphate	$Ca(H_2PO_4)_2$
Dicalcium phosphate	$Ca_2(HPO_4)_2 = CaHPO_4$
Tricalcium phosphate	$Ca_3(PO_4)_2$

These formulas show clearly that in monocalcium phosphate only 1 of the hydrogen ions has been replaced by a calcium ion, in dicalcium phosphate 2, and in tricalcium phosphate all have been replaced. The presence of the hydrogen ion greatly influences the solubility of the compound which contains it, as well as the pH value of the resulting solution. Table 19.1 shows the relative solubility of these three calcium phosphates as well as the pH value of the solutions, though the figures given can serve only as indications, since the addition of water to phosphates results in various other changes which are influenced also by the temperature.

TABLE 19 1. THE DEGREE OF SOLUBILITY OF CALCIUM PHOSPHATES AND THE pH VALUE OF THE SOLUTION

Type of phosphate	Formula	Solubility, g/liter	pH value
Monocalcium phosphate	$Ca(H_2PO_4)_2$	1,000.0	2.6
Dicalcium phosphate	$CaHPO_4$	0.25	7.1
Tricalcium phosphate	$Ca_3(PO_4)_2$	0.005	6.8

This table shows that monocalcium phosphate is very highly soluble as well as extremely acid. Dicalcium phosphate is only slightly soluble and is neutral in reaction, and tricalcium phosphate is nearly insoluble and likewise neutral. Monocalcium phosphate is added to the soil when superphosphate is applied. Tricalcium phosphate is added when apatite, phosphate rock, or bone meal are applied.

Action of Superphosphate on Soil

The question immediately presents itself: "Does the addition of superphosphate acidify the soil?" As everyone who has used superphosphate knows from experience, this is not the case. The reason is that in the presence of calcium ions—which, in the average cultivated soil, are usually present in ample amounts—the acid monocalcium phosphate is immediately converted into the neutral dicalcium phosphate, as follows:

(1) The conversion of monophosphate in the presence of calcium proceeds according to the following equation:

$$\underset{\text{monocalcium phosphate}}{Ca(H_2PO_4)_2} + \underset{\text{calcium carbonate}}{CaCO_3} = \underset{\text{dicalcium phosphate}}{2CaHPO_4} + \underset{\text{water}}{H_2O} + \underset{\text{carbon dioxide}}{CO_2}$$

(2) When the soil atmosphere has a high content in carbon dioxide, calcium bicarbonate is formed and monocalcium phosphate is converted as follows:

$$\underset{\text{monocalcium phosphate}}{Ca(H_2PO_4)_2} + \underset{\text{calcium bicarbonate}}{2Ca(HCO_3)_2} = \underset{\text{dicalcium phosphate}}{2CaHPO_4} + \underset{\text{calcium carbonate}}{CaCO_3} + \underset{\text{water}}{3H_2O} + \underset{\text{carbon dioxide}}{3CO_2}$$

(3) The conversion of monocalcium phosphate in alkaline soils containing sodium carbonate:

$$\underset{\substack{\textit{monocalcium}\\ \textit{phosphate}}}{Ca(H_2PO_4)_2} + \underset{\substack{\textit{sodium}\\ \textit{carbonate}}}{Na_2CO_3} = \underset{\substack{\textit{dicalcium}\\ \textit{phosphate}}}{CaHPO_4} + \underset{\substack{\textit{disodium}\\ \textit{phosphate}}}{Na_2HPO_4} + \underset{\textit{water}}{H_2O} + \underset{\substack{\textit{carbon}\\ \textit{dioxide}}}{CO_2}$$

(4) In strongly alkaline soils with a high content of calcium carbonate, dicalcium phosphate may be converted into tricalcium phosphate as follows:

$$\underset{\substack{\textit{dicalcium}\\ \textit{phosphate}}}{2CaHPO_4} + \underset{\substack{\textit{calcium}\\ \textit{carbonate}}}{CaCO_3} = \underset{\substack{\textit{tricalcium}\\ \textit{phosphate}}}{Ca_3(PO_4)_2} + \underset{\substack{\textit{calcium}\\ \textit{bicarbonate}}}{Ca(HCO_3)_2}$$

Monocalcium phosphate cannot exist in the soil in the presence of calcium or at a pH value above 5. Contrary to frequent statements, it can form or persist only at a very low pH value (below pH 4).

Iron and Aluminum Phosphates. This might suggest that in acid soils the application of superphosphate (monocalcium phosphate) would be particularly effective. In reality, this is not the case under average conditions, since below pH 5 the various commonly present iron and aluminum compounds are highly soluble, and, through double decomposition (page 161), cause the formation of practically insoluble iron and aluminum phosphates. In consequence, soils of low pH value usually have an extremely low content in available phosphate, and the average crop plant is likely to suffer from phosphate deficiency in such soils. Liming is the best remedy.

When tricalcium phosphate (in phosphate rock) is added to a soil with a pH between 6 and 7.5, it is likewise converted into the dicalcium phosphate through combined hydrolysis and carbonation, the carbon dioxide of the soil atmosphere being responsible for the latter.

(1) The conversion of tricalcium phosphate into the dicalcium phosphate proceeds theoretically as follows:

$$\underset{\substack{\textit{tricalcium}\\ \textit{phosphate}}}{Ca_3(PO_4)_2} + \underset{\textit{water}}{H_2O} + \underset{\substack{\textit{carbon}\\ \textit{dioxide}}}{CO_2} = \underset{\substack{\textit{dicalcium}\\ \textit{phosphate}}}{2CaHPO_4} + \underset{\substack{\textit{calcium}\\ \textit{carbonate}}}{CaCO_3}$$

(2) In the presence of calcium bicarbonate (when the soil atmosphere has a high content of carbon dioxide):

$$\underset{\substack{\textit{tricalcium}\\ \textit{phosphate}}}{Ca_3(PO_4)_2} + \underset{\substack{\textit{calcium}\\ \textit{bicarbonate}}}{Ca(HCO_3)_2} = \underset{\substack{\textit{dicalcium}\\ \textit{phosphate}}}{2CaHPO_4} + \underset{\substack{\textit{calcium}\\ \textit{carbonate}}}{2CaCO_3}$$

Dicalcium Phosphate as Main Source of Plant Phosphorus

Once more, dicalcium phosphate results, and the conclusion is unavoidable that it is actually the dicalcium phosphate which serves as the main source of phosphate in plant nutrition. Its relatively low solubility is perfectly sufficient to assure satisfactory phosphate availability, and besides many organic acids, which are normally present in the soil, as well as various ammonium salts (see page 224), certain constituents of humus and the activity of soil microorganisms serve to increase its solubility very appreciably.

Ammonium Phosphate

In soils containing a fair amount of humus, ammonium phosphate is usually present. Though the amounts generally are relatively small, the ready solubility of this compound at all pH levels and its nearly complete dissociation leave no doubt that it contributes to the natural phosphate nutrition of plants.

INFLUENCE OF SOIL pH VALUE ON PHOSPHATE AVAILABILITY

The most important factor in phosphate availability is undoubtedly the pH value of the soil, since on it depends largely what kinds of phosphates will be present. Dicalcium phosphate, which is the most readily available one, will be found only at pH values from 6 to 7.8. Below pH 6, aluminum and iron become increasingly soluble, resulting in the formation of insoluble aluminum and iron phosphates. Above pH 7.5, tricalcium phosphate is formed, which also is practically insoluble.

Magnesium phosphates behave similarly to the calcium phosphates, but, since magnesium never is as abundant in the soil as calcium, this type of phosphates need not be treated in further detail.

Most Favorable pH Range for Phosphorus Nutrition

The most favorable soil reaction for the phosphorus nutrition of plants is between pH 6 and 7.5, and phosphate can most readily be made available for the average crop plant by adjusting the soil pH value to this range.

TABLE 19.2. THE PHOSPHATE COMPOUNDS WHICH DOMINATE AT DIFFERENT pH LEVELS

pH range	Phosphate mainly combined with	Solubility
3–4	Iron and aluminum	Insoluble
5–6	Iron	Practically insoluble
6–7.8	Calcium (as dicalcium phosphate)	Sufficiently soluble
Above 7.8	Calcium (as tricalcium phosphate)	Practically insoluble
	Also sodium (as disodium phosphate)	Soluble

Table 19.2 gives a convenient review of the phosphate compounds which predominate at the various pH levels. This will explain their conversion as the pH changes.

Sodium Phosphate

Sodium, which is almost sure to be present in a soil with a pH above 8, causes the formation of the readily soluble sodium phosphate. Actually, the high solubility of this compound is a disadvantage because it renders it very susceptible to leaching, a fact which must be taken into account when semiarid and sodium-containing alkaline soils are artificially irrigated. In a highly alkaline calcium soil, correct application of superphosphate in bands on the surface so as to keep it away from the fixing power of such a soil can assure its effectiveness.

INFLUENCE OF MICROORGANISMS ON PHOSPHORUS AVAILABILITY

Microorganisms contribute to phosphate availability by means of the various acids which they produce and which increase the solubility of otherwise insoluble or nearly insoluble phosphate compounds. It has been estimated that about 35 per cent of all the soil bacteria are able to dissolve tricalcium phosphate, and, since the conversion takes place most actively in the immediate vicinity of the root tips where, owing to plant-root excretions, the responsible microorganisms are most plentiful, it is by no means negligible. Cultivation of plants in sterilized soil has proved that the solvent action of the roots themselves was insignificant.

Various complex organic phosphorus compounds, such as lecithin, nucleic acids, phytin, and others, are commonly contained in organic matter. These are acted upon by various bacteria and fungi which are able to break them down—usually by means of enzymes such as phytase—and to liberate the phosphorus as phosphate or as phosphoric acid.[1]

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[1] Waksman, S. A., "Soil Microbiology," pp. 235–240, New York, John Wiley & Sons, Inc., 1952.

20. THE STORY OF POTASSIUM

Potassium is very common in nature, though it never occurs in elemental form. It is a component of granites and of gneiss as well as of most other igneous rocks, and it has been estimated that 3 per cent of the earth's crust (the lithosphere) is composed of potassium. In consequence, the average mineral soil contains rather large total amounts—as much as 50,000 lb/acre or even more—mainly as a constituent of feldspars, micas, and other silicate minerals. It was shown previously (page 158) how these minerals decompose under the influence of chemical reactions, and how this decomposition results in converting potassium as well as various other elements into soluble substances, so that they become available to plants.

Some of the potassium-containing feldspar minerals, such as leucite (in Wyoming), occur in very extensive deposits and can be mined. So far, however, no method for the exploitation of these sources has been devised which is economical enough to compete with the commercial production of potassium fertilizers from salt deposits.

Greensand, Potassium Shale, and Alunite

Other important silicate minerals which contain potassium are the so-called greensands, which occur particularly in New Jersey, Delaware, Maryland, Virginia, and North Carolina; the potassium shales of Georgia, Ohio, and Minnesota; and the alunite deposits which are found in Utah as well as in several other Western states.

Greensand is believed to have originated from biotite under the influence of sea water, large deposits of it having actually been located on the sea bottom. Its essential component is glauconite ($KFeSi_2O_6 \cdot nH_2O$), which, as the formula shows, is a hydrated silicate of potassium and iron, but it contains admixtures also of aluminum, phosphorus, and other elements. The material is earthy or sandy in texture and can be mined by power shovel from open pits, but its processing, which mainly involves treatment with sulfuric acid in order to obtain potassium sulfate, is rather expensive, its potassium content being only about 2.2 to 8 or 9 per cent.

The location of these huge deposits so close to the principal consuming areas gives them considerable importance. It appears, however, that exploitation can become economical only if the large amounts of wastes which unavoidably result can be turned into usable by-products. This problem, so far, has been solved only partially.

Other large potential sources of potassium are the Georgian potassium shales and alunite. Methods to process the latter, which is a hydrated basic sulfate of potassium and aluminum, usually also containing silica, have been worked out successfully. The extraction of potash from potassium shale, though promising of an early solution, is still under investigation.

Origin of the Name "Potassium"

All plants contain relatively large amounts of potassium and ashes of white ash (*Fraxinus americana*) are reported to be particularly rich in it (34.7 per cent). The name of the element actually is derived from the word "pot ashes," since it was obtained through leaching wood ashes in pots, a procedure which results in the separation of potassium carbonate. For the home manufacturer of soap, the required potassium is still frequently obtained in this primitive manner. When wood ashes—which may contain from 10 to 34 per cent potassium oxide—are applied to the soil, they provide readily available potassium but are rather highly alkaline, a fact which must be taken into consideration. Germinating seeds, for instance, may be harmed by wood ashes.

Potash from Kelp

A material very similar to the above-mentioned potash is obtained through the burning of large seaweeds called kelp. This procedure, which is practiced to a certain extent on the Pacific coast of North America as well as on the English Channel Islands, in Japan, and elsewhere, actually is rather expensive, since the raw material consists of as much as 80 per cent water and only a relatively small ash residue remains. The latter has a content of approximately 30 per cent potassium carbonate. By-products such as iodine help somewhat to defray the cost. The uncertainty of the kelp harvest contributes further to rendering this source of potassium of rather minor importance. (See page 261 for the use of seaweed as green manure.)

In southern Russia, where large areas are planted to sunflowers for oil production from the seeds, the stalks are burned after harvest, and potash is extracted from the ashes. Since production is reported to amount to over 20,000 tons/year, this represents a valuable by-product.

Sea-Water Content of Potassium

Sea water contains from 1 to 2 per cent potassium salts, and, where such water evaporates, with the other saline components crystallizing out, potassium salts accumulate in the remaining solution. In various regions of the world, which in long-bygone ages were covered by the sea, this process has resulted in very extensive deposits of potassium compounds.

The manner in which this happens parallels closely the sequence of events when sea water is evaporated artificially in order to obtain salt. In the artificial process, as the solution thickens, the common salt [sodium chloride ($NaCl$)] crystallizes out first, and the remaining brine, which is rich in potassium and magnesium salts, is drawn off because of the bitterness which the magnesium would impart to the salt. When evaporation continues under natural conditions, the magnesium and potassium salts eventually crystallize also. This is why natural potassium salt deposits usually occur overlying large deposits of common salt. Because of this behavior of the potassium salts, the brine of certain salt lakes (in Nebraska, Utah, Tunisia, and the Near East) is rich in potassium, which renders it usable as a source in the manufacture of potassium fertilizers.

Location of Potassium Salt Deposits

Some of the largest potassium salt deposits as well as those most extensively exploited commercially are in Germany, which, before World War I, produced almost 75 per cent of the world's output of potassium fertilizer. Others are in France (near Mulhouse), in Poland (near Kalusz), in the Near East (the shores of the Dead Sea), and elsewhere. Some of the best-known deposits in the United States are in California (the nearly dry Searles Lake, an area of 7,500 acres), in Nebraska (the salt lakes in the sand-hill region) and in Utah (the Great Salt Lake). Very extensive deposits have been found also in New Mexico and in various parts of Texas which latter, so far, are still largely in the exploratory stage.

Minerals Containing Potassium

The compounds in which potassium occurs in these deposits are usually double or triple salts, such as carnallite ($MgCl_2 \cdot KCl \cdot 6H_2O$), kainite ($KCl \cdot MgSO_4 \cdot 3H_2O$ or $MgSO_4 \cdot K_2SO_4 \cdot MgCl_2 \cdot 3H_2O$), polyhalite $K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$), and others. See page 310.) As can be seen from the formulas, these minerals contain potassium either as chloride or as sulfate, and it is in either of these two compounds that potassium is most commonly applied as a fertilizer.

Potassium salts can, of course, also be extracted directly from sea water, which contains inexhaustible supplies, but this possibility—though it is under investigation—is not being seriously exploited as yet.

Potassium Nitrate

Potassium nitrate (niter, Bengal saltpeter, KNO_3) occurs in fairly large natural deposits in Spain, Egypt, Persia, and India. It has been discovered also in the caverns of Kentucky and Tennessee as well as in the Mississippi Valley. This same compound forms naturally in the soil when organic matter decomposes and nitrifying bacteria produce nitrate in the presence of soluble potassium compounds. Artificially, it is produced from sodium nitrate and potassium chloride through double decomposition, according to the equation $NaNO_3 + KCl = KNO_3 + NaCl$. A certain amount of potassium nitrate is obtained when raw Chile saltpeter is refined.

Industrial Wastes as Sources of Potassium

Other sources of potassium, which are commercially exploitable but are of minor importance in comparison with natural deposits, are certain industrial wastes, such as the flue dust from cement kilns or from iron-ore blast furnaces. This material contains from 3 to 13 per cent potassium (mainly as chloride, sulfate, and carbonate), and it has been estimated that for each barrel of cement produced, 2 to 5 lb of potassium might be recovered in the form of potassium sulfate.

The wastes resulting from the distillation of cane-sugar molasses in industrial alcohol plants or from the refining of sugar-beet molasses may likewise be utilized, since the ash to which they are readily reduced has a content of 33 to 35 per cent potassium oxide. So far, only a very few of the existing cement and sugar factories actually do recover potassium as a by-product, but, if this were to become a general practice, definitely worth-while amounts could be made available.

Nature of Soil Governing Potassium Content

The ions of soluble potassium salts are adsorbed and held rather firmly by the soil colloids, which means that, in clay or loam soils containing a fair amount of colloid humus or of mineral colloids, potassium deficiency is much less likely to occur than in sandy soils with a low base-exchange capacity. (See page 76 for base-exchange capacity.)

Behavior of Soil Potassium

Field observations over extended periods of time have revealed the peculiar phenomenon that the soil content of available potassium remains at a fairly constant level from year to year, in spite of continuous loss through consumption by growing plants and through leaching caused by rain. The generally accepted reason for this highly significant behavior of soil potassium is the development of an equilibrium between the available and the unavailable potassium which establishes and maintains itself automatically. This means that, as soon as some of the available potassium is withdrawn through consumption or leaching, a corresponding portion of the so-far unavailable potassium (from the finely dispersed silicate minerals) is brought into solution—through the action of water and carbon dioxide—and appears in the soil solution or is adsorbed by the soil colloids.

This equilibrium can be expressed by the following equation: unavailable potassium $\rightleftharpoons$ exchangeable or dissolved potassium. (The double arrows ($\rightleftharpoons$) mean that the conversion can proceed in either direction, depending on circumstances.)

Practical Consequences. It is of the greatest importance for proper treatment of the soil that this behavior of soil potassium be thoroughly understood, since it has the following highly significant consequences:

(1) The level of available potassium characteristic for any given soil depends upon the nature of the soil—its composition and its colloidal properties. What the characteristic level is in each case can be determined only by means of soil analysis.

(2) In case the natural potassium level of a soil is below the optimum desirable for the plants to be grown, it is possible to raise it through the addition of potassium fertilizer, but it must be realized that such an application will result in the establishment of a new equilibrium, which means that part of the added potassium salt will immediately be converted into unavailable forms. In consequence, one has to add considerably more potassium fertilizer, to reach the desired level, than the difference between the old and the new level seems to warrant. (See page 313 for application of potassium fertilizer.)

(3) Because of the fact that the newly established higher potassium level is backed up by reserves, which are ready to go into solution as soon as some of the available potassium is used, one potassium fertilizer application will, in many instances, be sufficient for a number of

years. Soil analysis, after harvest or before the next crop is sown, will show clearly whether the potassium level has remained steady or has dropped lower than desirable. Needless expense may thus be avoided.

Effect of Potassium Salts on Soil pH Value

The claim has been made repeatedly that application of potassium salts (potassium chloride or potassium sulfate) lowers the pH value of the soil, in spite of the fact that both of these salts themselves are neutral in reaction. The facts are that potassium chloride (muriate of potash) in low concentration, or in the comparatively small amounts applied most commonly, has no effect on soil pH, but when large amounts are applied, it is likely to cause mild alkalinization. The application of potassium sulfate, on the other hand, does have a mildly acidifying residual action, the extent of the lowering of the pH value depending upon the nature of the soil and on its content of calcium carbonate. (See page 329 for an explanation of this behavior of the two most commonly employed potassium salts.)

21. THE STORY OF CALCIUM

KINDS OF CALCIUM COMPOUNDS

This element, with the chemical symbol Ca, is best known from one of its compounds, the much-employed "lime" (CaO, calcium oxide, or "burned lime"), but it must be emphasized that the term *lime* is also applied to various other calcium compounds. Naturally, this creates confusion, since no two of the different calcium compounds behave alike when they are added to soil. It is essential to distinguish sharply between such calcium compounds as burned lime (CaO, calcium oxide, or quicklime); hydrated lime [$Ca(OH)_2$, calcium hydroxide, or slaked lime]; carbonate of lime ($CaCO_3$, calcium carbonate, or limestone); and sulfate of lime ($CaSO_4$, calcium sulfate, gypsum or land plaster). All of these are further explained below.

Calcium compounds are by no means useful only for "sweetening" (neutralizing) acid soils. The influence of calcium in the soil is manifold and far reaching, and best results in soil treatment and plant culture can be achieved only if the various actions and reactions for which this element is responsible are taken into account.

ORIGIN OF SOIL CALCIUM

The element calcium combines readily with almost every known acid, forming a vast number of compounds, and for this reason it does not occur in nature in its elemental state. In the form of compounds, however, it is one of the main components of the lithosphere, and it ranks fifth among other elements as far as amounts estimated to be present on earth are concerned. Which are the naturally occurring calcium compounds of greatest importance for soil fertility, and how did they come into being in the first place? The answer to the last question will tell, at the same time, how and why soil calcium supplies may or may not maintain themselves under varying conditions.

The five main groups of calcium-containing minerals are discussed below.

Silicate Minerals

Silicate minerals include various types of feldspar, such as anorthite ($CaAl_2Si_2O_8$); amphiboles (metasilicates of calcium and magnesium), such as hornblende, tremolite, actinolite, etc.; and pyroxenes, such as augite and others.

Such silicate minerals are included in various types of igneous and metamorphic rocks (see page 152) and must be considered as the original source of the calcium contained in the soil. When silicates decompose under the influence of water and carbon dioxide—hydrolysis, hydration, and carbonation—clay is evolved and calcium and magnesium as well as other alkalis (sodium and potassium) are freed in the form of carbonates or bicarbonates (page 159). This process may be illustrated by the following equation:

$$\underset{\substack{\textit{anorthite}\\\textit{(calcium-}\\\textit{aluminum}\\\textit{polysilicate)}}}{\mathrm{CaAl_2Si_2O_8}} + \underset{\substack{\textit{carbonic}\\\textit{acid}}}{\mathrm{H_2CO_3}} + \underset{\textit{water}}{\mathrm{H_2O}} = \underset{\substack{\textit{clay}\\\textit{substance}}}{\mathrm{H_4Al_2Si_2O_9}} + \underset{\substack{\textit{calcium}\\\textit{carbonate}}}{\mathrm{CaCO_3}}$$

Surplus carbon dioxide converts the calcium carbonate into the readily water-soluble calcium bicarbonate which, when leached out and under loss of carbon dioxide, is redeposited elsewhere as calcium carbonate (limestone).

Calcium Carbonate Minerals

Calcium carbonate minerals exist in wide variety and originate as a secondary step, once calcium carbonate has been formed in the above described manner.

Types of Calcite Crystals. The variety results mainly from the many different ways—over 300 have been recognized—in which calcite (pure calcium carbonate) may crystallize. Occasionally, large clear crystals of varying color result, such as the transparent crystals of Iceland spar, so named because they were first observed in Iceland. Another specific type is aragonite (first discovered at Aragon, Spain), which is found most commonly in caves or in mine shafts and which usually forms thin, spire-shaped crystals. Sometimes, however, aragonite forms rather large masses, the so-called Mexican and Algerian onyx, though true onyx is a quartz mineral. Other forms of calcite are oölite, composed of minute rounded limestone concretions, and pisolite, in which the limestone spheres are as large as peas. The stalactites and stalagmites found in caves—the former hanging iciclelike from the roof and the latter rising from the floor—likewise consist of calcite, having been deposited slowly by dripping water.

Limestone. The most common form of cryptocrystalline, or microcrystalline, calcite is limestone, of which a great many different types are distinguished, varying in compactness (hardness) as well as in color and in the manner of their formation. The only thing common to all limestones is that they originate as sediment from water, though they may have been deposited from sea water or from fresh-water lakes, from calcareous springs (travertine), or, as in the case of calc-tufa, from hot mineral springs. Very common are combinations of calcium carbonate with magnesium carbonate, called *dolomite* when the magnesia content amounts to at least 21 per cent, or *dolomitic limestone* when the magnesia content is over 5 per cent but less than 21 per cent. Limestone, dolomitic limestone, and dolomite frequently form extensive mountain ranges, which, as the warping and tilting of the limestone layers show, were raised or folded up after the limestone had been deposited from water. The development of high temperatures, which frequently accompanied such violent upheavals, and the chance burying of part of the limestone at considerable depth, where it was subjected to great pressure, resulted occasionally in the production of marble. (See page 152.)

Ground limestone has many industrial uses, some 10 million tons a year of it being employed in the United States alone to serve as flux for removal of silica in the smelting of iron ore and other ores.

CHALK. Chalk, which likewise is calcium carbonate but which is soft and friable, originated from marine deposits of the microscopically small, lime-encrusted shells or skeletons of tiny primitive animals (Foraminifera, belonging to the Protozoa, page 57) which occurred in enormous numbers especially during the Tertiary period. Under special conditions, such completely organic deposits, which may include ground-up coral as well as the shells of various marine mollusks, also were compacted into limestone.

MARL. Marl originates as ooze at the bottom of fresh-water lakes, eventually forming beds or strata. It represents a mixture of chalk, gypsum, sand, and clay, together with calcium carbonate, which was precipitated directly from the water. It usually contains also small shells of mollusks as well as deposits of certain lime-encrusted algae, such as species of *Chara* and *Nitella.* Fossil remains of larger animals may be included also.

Marl commonly is overlaid with peat or muck or both and usually contains also a fair amount of available ammonium (0.2 to 0.5 lb/ton or approximately 0.02 per cent).

CALICHE. Caliche, a Spanish word, refers to the crust or succession of crusts of calcium carbonate which occasionally form within or on top of stony arid soil. Such crusts nearly always contain also sodium carbonate (Arizona).

Burned Lime and Hydrated Lime. When calcium carbonate is brought to white heat (850 to 900°C) in a current of air, the carbonic acid is removed and calcium oxide or quicklime (CaO) results. In contact with water, quicklime evolves much heat and, increasing in volume, is converted into calcium hydroxide or hydrated lime [$Ca(OH)_2$]. The various uses made of quicklime are based on this reaction with water. Very large amounts of quicklime are produced, for instance, in the manufacture of cement, a process which requires the inclusion of a certain proportion of clay. The building industry uses quantities of quicklime in plastering —for which purpose it may be mixed with gypsum and other substances— or as a component of stucco.

The amounts of hydrated lime used in agriculture are comparatively small, and, as explained elsewhere (page 408), hydrated lime actually is a rather undesirable material for agricultural purposes, the much cheaper ground limestone being greatly superior and much safer.

Calcium Sulfate Minerals

The most common form in which calcium sulfate occurs in nature is as gypsum ($CaSO_4 \cdot 2H_2O$), 2 molecules of water being attached to each molecule of calcium sulfate. (See water of crystallization, page 156.)

Calcium Sulfate Crystals. When free of water of crystallization, calcium sulfate is called anhydrite, and in this form it may crystallize in various ways. When clear, transparent crystals develop, the mineral is known as *selenite,* and it is called *satin spar* when it forms a cleavable, fibrous, opalescent mass. When it forms a compact, finely granular mass, usually pure white in color, the mineral is called *alabaster.* The latter name, however, is applied also to a translucent type of calcium carbonate which occasionally forms in limestone caves. Calcium carbonate alabaster usually has a yellowish milky color, sometimes marked with darker streaks, and is harder than gypsum alabaster, the latter being so soft that it may be cut with a knife. An excellent quality of gypsum alabaster is mined in Italy as well as in England and is carved extensively into statuettes and vases (so-called Florentine marble).

Plaster of Paris. When gypsum is heated, part of its water of crystallization (approximately 75 per cent) is evaporated, and plaster of Paris results. As long as the heat applied does not exceed 500°F, plaster of Paris retains the power to recombine with water, forming then a hard, noncrystalline mass. This property renders plaster of Paris suitable for making masks, molds, and casts. When certain other substances are added, still greater hardness may be imparted to plaster of Paris. Parisian cement, for instance, contains a certain amount of borax, and marble cement contains alum and soda.

Origin of Gypsum. Extensive natural deposits of gypsum originate most commonly through the evaporation of sea water, since most of the calcium contained in sea water is in the form of calcium sulfate. The solubility of calcium sulfate being lower than that of most other salts present in sea water, it is precipitated during the earliest stages of evaporation, and, in consequence, gypsum deposits quite frequently occur under deposits of rock salt (sodium chloride).

Gypsum is formed in nature also in volcanic regions, when various calcium minerals are exposed to the influence of sulfuric acid. The latter develops through oxidation of the sulfur dioxide present in the volcanic gases. A similar reaction may occur, though usually on a much smaller scale, under nonvolcanic conditions, when sulfuric acid develops through the oxidation of pyrite (iron disulfide) in contact with air. The following equation illustrates this process:

$$\underset{\text{pyrite}}{4FeS_2} + \underset{\text{oxygen}}{15O_2} + \underset{\text{water}}{8H_2O} = \underset{\substack{\text{ferric}\\\text{oxide}}}{2Fe_2O_3} + \underset{\substack{\text{sulfuric}\\\text{acid}}}{8H_2SO_4}$$

Gypsum originating in this manner usually contains a fairly large proportion of iron.

Use of Gypsum in Agriculture. Powdered gypsum is used in agriculture to ameliorate highly alkaline soils containing sodium. (See page 417.) Because it does not lower the pH value of acid soils, it may be used also to supply readily available calcium for nutrient purposes when the pH value of an acid soil is not to be interfered with (for instance, in the culture of cotton and soybeans). Under such conditions the application of 300 to 500 lb/acre of gypsum will suffice to correct a calcium deficiency.

Calcium Fluoride

Calcium fluoride (CaF_2), also called *fluorite* or *fluorspar,* is mentioned here mainly for completeness sake, its significance, if any, in the soil picture being not clear. Occurring in crystals or in solid masses, sometimes in extensive deposits, it is lustrous and translucent, or even transparent, and it may be white, yellow, green, red, blue, or brown in color. Massive deposits of calcium fluoride most commonly originate under volcanic conditions, when hydrofluoric acid, contained in the volcanic gases, acts on various calcium silicates. In the reaction which takes place, the developing gaseous silicon fluoride (SiF_4) escapes into the air and calcium fluoride remains behind as a solid deposit.

Fluoride in Soil Originating from Fluorapatite. Calcium fluoride is formed in the soil when fluorapatite [$CaF_2 \cdot 3Ca(PO_4)_2$]—a common component of igneous rocks—decomposes under the influence of carbonic acid. The ensuing process may be illustrated by the following equation:

$$\underset{\textit{apatite}}{CaF_2 \cdot 3Ca(PO_4)_2} + \underset{\substack{\textit{carbonic}\\ \textit{acid}}}{12H_2CO_3} = \underset{\substack{\textit{calcium}\\ \textit{fluoride}}}{CaF_2} + \underset{\substack{\textit{monocalcium}\\ \textit{phosphate}}}{3CaH_4(PO_4)_2} + \underset{\substack{\textit{calcium}\\ \textit{bicarbonate}}}{6CaH_2(CO_3)_2}$$

Both monocalcium phosphate and calcium bicarbonate are readily water soluble, though monocalcium phosphate is quickly converted into less soluble forms. Under conditions favoring leaching of the calcium bicarbonate, the difficultly soluble calcium fluoride may accumulate.

The presence of ammonium salts will increase the solubility of calcium fluoride and thus will make both the calcium fraction and the fluoride fraction more readily available to plants.

Calcium Phosphate Minerals

Calcium phosphate minerals are of very great importance in the plant-soil relationship, not only for their phosphorus content but also for the calcium fraction of the respective compounds. The calcium phosphates, however, are treated in considerable detail in other parts of this book (see pages 176, 208 and 209) so that further explanations here are not necessary.

INCREASED SOLUBILITY OF CALCIUM SALTS IN THE PRESENCE OF AMMONIUM SALTS

A matter of considerable biological significance is the increase in solubility of calcium salts in the presence of certain salts which ammonium forms with strong acids, such as ammonium sulfate and ammonium chloride. When either of these freely soluble salts dissolves and therewith dissociates, free acid is formed—in one case sulfuric acid and in the other hydrochloric acid. In consequence, the difficultly soluble calcium carbonate will be converted into either calcium sulfate or calcium chloride, both of which have a much higher solubility. The process which ensues may be illustrated by the following equilibrium equations:

$$\text{CaCO}_3 + \text{H}^+ + \text{OH}^- \rightleftharpoons \text{Ca}^{++} + \text{HCO}_3^- + \text{OH}^- \tag{1}$$

soluble part of calcium carbonate	*ions of water*	*ions resulting from the dissociation of calcium carbonate dissolved in water*

$$\text{NH}_4^+ + \text{Cl}^- \rightleftharpoons \text{NH}_3 + \text{H}^+ + \text{Cl}^- \tag{2}$$

ammonium chloride dissociated	*undissociated ammonia*	*ions of dissociated hydrochloric acid*

$$\text{CaCO}_3 + 2\text{NH}_4^+ + 2\text{Cl}^- \rightleftharpoons \text{H}_2\text{CO}_3 + 2\text{NH}_3 + \text{Ca}^{++} + 2\text{Cl}^- \tag{3}$$

calcium carbonate	*ammonium chloride*	*undissociated carbonic acid*	*undissociated ammonia*	*ions of calcium chloride*

The third equation shows that, because of the formation of the readily soluble and to a large part dissociated calcium chloride, the amount of calcium ions present in the solution is bound to increase. The conversion, naturally, is not absolute, since it is controlled by an equilibrium, and the amount of additional calcium becoming available depends upon the amount of ammonia present in the solution.

The whole process is further complicated by the fact that a certain amount of liquid can never contain more than a well-defined amount of a certain type of ions. When the saturation point is reached, dissociation of the respective dissolved compound discontinues. Therefore, calcium carbonate likewise will stop dissociating when this particular point is reached.

LIMIT TO WHICH CALCIUM CARBONATE CAN RAISE THE pH VALUE

Whether the Ca^{++} and CO_3^{--} ions, which fill the quota, come from calcium carbonate (limestone), which was added to the soil, or from other calcium salts or carbonates, which were present previously, does not matter at all. Naturally, when calcium carbonate remains undissociated—even if it is dissolved—no more OH^- ions enter the solution, and the pH value, therefore, remains unaffected and unchanged. In consequence—since other calcium salts and other carbonates are always present in soil—calcium carbonate never can produce in soil the pH value of pure calcium carbonate (9.5). Contributory to this phenomenon is the fact that the OH^- ions, which cause the rise in pH value when calcium carbonate dissociates, have to come from increased dissociation of the water, which latter sets up its own resistance, in contrast to calcium hydroxide [$Ca(OH)_2$] where the hydroxyl ions form a part of the compound itself. (See page 315 for further details on the behavior of calcium hydroxide.)

CALCIUM BICARBONATE

Formation in the soil of the readily soluble calcium bicarbonate [$Ca(HCO_3)_2$] depends upon the amounts of carbon dioxide present. (See page 175 for requisite carbonic acid.) Since considerable amounts of carbon dioxide are evolved when organic matter decomposes, the incorporation of organic matter in the soil assists in rendering calcium more readily available. This benefit is obtained in addition to the above-described action of ammonia which is produced during this same chain of biological decomposition processes. The use of calcium carbonate (ground limestone) for the purpose of neutralizing acid soils is described in full in Part VII (page 409), but the importance of calcium as a plant nutrient, which must not be overlooked, requires some further explanations.

BENEFITS OF LIMING

It has been stated repeatedly in soil literature that the improvement of yields resulting from lime application to acid soils very frequently is due not so much to the raising of the pH value as to the added supply of readily available calcium. There is a good deal of truth in this statement, because some acid soils of highly organic composition can frequently not be neutralized at all, except with such huge amounts of ground limestone that the attempt is not practical. Yet, the addition of a fair amount of ground limestone (1 to 1½ tons/acre) to such a soil—even when this does not result in raising the pH value much above 5—may produce an unmistakable improvement in the development of the plants. This is because the average healthy plant requires relatively large amounts of calcium, absorbing by weight approximately twice as much calcium as nitrogen or potassium and four to eight times as much as phosphorus, while highly acid soils commonly have a very low calcium content.

Calcium as a Plant Nutrient

Within the plant, calcium appears to act mainly as a translocation regulator, which means that it assists in controlling the absorption of other substances as well as in their distribution throughout the tissues.

Upsetting of the calcium balance results in various troubles. Lack of calcium causes stunting in many plants, presumably because it renders inefficient the absorption and utilization of nitrogen. The presence of overlarge amounts of available calcium lowers the uptake of potassium and interferes with the utilization of iron and manganese. With certain plants, calcium appears to control the utilization of potassium, the most favorable proportion of calcium to potassium depending on length of daylight. Calcium furthermore appears to control the uptake of magnesium as long as the respective amounts of available magnesium and calcium which are present do not exceed the proportion 1:3. Larger amounts of magnesium in relation to calcium are likely to result in trouble.

Decomposition of Organic Matter

Most lower fungi as well as bacteria are benefited by the application of calcium when the calcium content of the soil is low. This effect becomes apparent through speedier decomposition of the soil organic matter. Such a speed-up is not necessarily advantageous, since it may lead to a needlessly fast dissipation of organic matter, a fact which has to be taken into account when soils are limed.

LOW pH VALUE NO CRITERION OF SOIL CALCIUM CONTENT

In conclusion, it may be pointed out that the pH value of a soil, by itself, does not indicate the amount of calcium which may or may not be present. Calcium sulfate, which is frequently present, exerts no appreciable influence on the pH value of an acid soil, and neither do calcium chloride or calcium nitrate. A pH reading, therefore, provides no clue as to the likely presence or absence of any of these calcium compounds. Only a soil analysis for calcium can supply the correct information, and only a lime-requirement test will make it possible to establish how much ground limestone per acre must be applied to raise the pH value of an acid soil to a more favorable level.

22. THE STORY OF SULFUR

NATURAL DEPOSITS OF ELEMENTAL SULFUR

Elemental sulfur, a yellow metalloid, occurs in many parts of the world. Usually it is found in nature in volcanic regions or in regions which, during some period of their geologic past, were highly volcanic. Until rather recently most of the sulfur in world commerce—including that sold commercially in the United States—came from Sicily or from the Chilean Andes, though sulfur is mined also in Mexico, China, Japan, India, the Philippine Islands, and Iceland. Extensive American deposits which are being mined exist in southern Utah, and others of lesser extent are in California and Nevada, but most of the American supply now comes from Louisiana and Texas, where large deposits are being exploited. World supplies, however, are not unlimited. Increased world consumption in recent years, without corresponding increase in production, has caused concern in the fertilizer industry of the United States.

SULFUR OXIDATION

Elemental sulfur melts at a temperature slightly above the boiling point of water but is not soluble in water. It is for the latter reason that elemental sulfur is inert and, in itself, has no effect on soil or plants. It becomes more or less water soluble and, therewith active, only after oxidation. The ease with which sulfur oxidizes, however, is one of its most outstanding characteristics and is also the reason why it burns so readily. Burning, in fact, is little else than very rapid oxidation.

Normal, slow oxidation without heat or flame, such as proceeds in the soil, results in the production of sulfurous or sulfuric acid. When these acids combine with various bases—which they do very readily—salts are formed. These salts are called sulfites or sulfates, depending upon their oxygen content.

The Sulfides

With various metals, sulfur also readily forms oxygen-free compounds, the sulfides (pyrites for instance). As indicated, the main difference between sulfites and sulfides—aside from their origin—is that the latter do not contain oxygen. Many of the sulfides are valuable ores for the other elements they contain besides sulfur, such as sulfide of lead (galena), sulfide of mercury (cinnabar), and sulfide of zinc (zinc blende or sphalerite). Hydrogen sulfide (H_2S), importantly involved in soil sulfur conversion, will be discussed presently. The sulfites, salts of sulfurous acid (H_2SO_3), are of no interest for an understanding of soil or of soil sulfur and will not be discussed here.

The Sulfates

As far as soil is concerned, the sulfates (the salts of sulfuric acid, H_2SO_4), which usually are quite readily water soluble, are of greatest interest. Among them, calcium sulfate or gypsum ($CaSO_4 \cdot 2H_2O$) is undoubtedly the most important as well as the one which is most commonly present in the soil in rather large amounts.

THE SULFUR CYCLE

Sulfate is intimately involved in the vitally important process of cell division, which means in the active growth of plants or animals. This explains why sulfate is a required nutrient, and its behavior in the soil as well as the factors responsible for making it available to plants thus become of absorbing interest. Most intriguing is the similarity between the sulfur cycle and the nitrogen cycle, though one important difference must not be overlooked. Even in cultivated soils, mineralized sulfur is usually present in rather large amounts (250 lb to as much as 1,000 lb/acre under average conditions). As has been shown, this is not the case with nitrogen. When decomposing organic matter, however, is considered as a sulfur source for higher plants—and there is no doubt that this is an important source—the similarity between the behavior of soil nitrogen and soil sulfur becomes very apparent.

Sulfur Derived from Organic Matter

When organic matter is decomposed by various microorganisms, the sulfur-bearing fraction is separated, either by being assimilated by various microorganisms or by being further decomposed by bacteria, until the inorganic hydrogen sulfide (H_2S) results. Either in combination with water and oxygen or with oxygen alone, hydrogen sulfide quickly oxidizes into water and elemental sulfur. This is a purely chemical reaction which proceeds readily without the interaction of bacteria, though various bacteria (*Thiothrix, Thiobacillus,* and others) do assimilate hydrogen sulfide and produce either elemental sulfur or sulfuric acid directly. Whatever process, chemical or biological, may be responsible for this conversion under varying circumstances, the elemental sulfur which results is further oxidized into sulfuric acid by autotrophic bacteria. (See page 52.) Sulfuric acid then combines with various bases to form sulfates. This highly significant chain of reactions may be further illustrated by means of the following equations:

$$(1)\qquad \underset{\substack{\textit{hydrogen}\\ \textit{sulfide}}}{2H_2S} + \underset{\textit{oxygen}}{O_2} = \underset{\textit{water}}{2H_2O} + \underset{\textit{sulfur}}{S_2}$$

$$(2)\qquad \underset{\textit{sulfur}}{S_2} + \underset{\textit{oxygen}}{3O_2} + \underset{\textit{water}}{2H_2O} = \underset{\substack{\textit{sulfuric}\\ \textit{acid}}}{2H_2SO_4}$$

$$(3)\qquad \underset{\substack{\textit{sulfuric}\\ \textit{acid}}}{H_2SO_4} + \underset{\substack{\textit{calcium}\\ \textit{carbonate}}}{CaCO_3} = \underset{\substack{\textit{calcium}\\ \textit{sulfate}}}{CaSO_4} + \underset{\textit{water}}{H_2O} + \underset{\substack{\textit{carbon}\\ \textit{dioxide}}}{CO_2}$$

The similarity to the behavior of nitrogen is striking. The evolution of the inorganic hydrogen sulfide, as the end product of the decomposition of organic matter, compares with the production of the inorganic ammonia in the nitrogen cycle. And, just as ammonia is oxidized by bacteria into nitric acid, which combines with bases to form nitrates, so is hydrogen sulfide oxidized into sulfuric acid from which sulfates are formed.

That part of the hydrogen sulfide which the microorganisms assimilate for the synthesis of proteins has to be decomposed once more when the bacteria die, before the sulfur becomes available again, in much the same manner as with ammonia.

Leaching of Sulfates

Both nitrates and sulfates are readily water soluble, and both, therefore, are exposed to leaching, though sulfates in general not quite as much as nitrates. In regions with high annual rainfall, however, such leaching of the sulfates may actually result in sulfur deficiency.

The Reduction of Sulfate to Hydrogen Sulfide

The similarity goes even farther. Just as nitrates may be reduced under anaerobic conditions (when oxygen is lacking) to elemental nitrogen, so sulfates may be used by bacteria as a source of oxygen, especially in soils which are waterlogged. This results in the production of hydrogen sulfide (H_2S), and the highly unpleasant odor of this gas is indeed quite characteristic of certain bog soils.

Soil Conditions Favorable for the Transformation of Sulfur

The eternal round of the sulfur cycle, from a simple inorganic state to complex organic compounds and back again and around once more, is thus made clear, and it has been shown that this cycle includes oxidation and reduction, synthesis into proteins, and the decomposition of proteins which contain sulfur. The soil conditions which favor a smooth progression of these processes are very much the same as those which favor ammonification and nitrification. These consist in the presence of organic matter, good soil aeration, a suitable temperature, and the presence of water up to a maximum of 50 per cent saturation.

CONSEQUENCES OF THE STEPS IN SULFUR TRANSFORMATION

Each one of the three steps, which represent the most important part of the soil sulfur transformation chain, and which were explained above by means of equations, has certain immediate consequences. These may be summed up as follows:

(1) The hydrogen sulfide, which develops in the soil and which would have toxic effects if it were to accumulate, is converted immediately and as quickly as it is formed into the harmless elemental sulfur.

(2) The oxidation of elemental sulfur results first of all in the production of sulfuric acid. When the elemental sulfur in question has originated from the decomposition of organic matter, this causes no appreciable acidification because of the complexity of the various other processes which go on simultaneously. Under average conditions the sulfuric acid is quickly converted into neutral or near-neutral sulfates. When elemental sulfur is added to the soil, however, a definite lowering of the pH value results. The time required for elemental sulfur (flowers of sulfur) to produce soil acidification depends on various circumstances, such as soil composition and climatic conditions, but the conversion

always proceeds rather slowly, and it may take as much as 3 years after sulfur has been incorporated before the effect on the soil becomes apparent. How much the pH is lowered and how long the increased acidity lasts will depend upon the buffering of the soil (see page 172) as well as upon the amount of sulfur added.

(3) The formation of sulfate results, in particular, in converting the alkaline and nearly insoluble calcium carbonate into the neutral and quite readily soluble calcium sulfate. This process serves to make calcium readily available to plants. Quite similar is the effect on other difficultly soluble bases, such as tricalcium phosphate in phosphate rock and potassium in carnallite, glauconite, or greensand. Sulfur thus is revealed as a widely useful member of nature's household beyond its service as an essential plant nutrient.

Some of the most commonly present or most frequently applied sulfates may be discussed in somewhat further detail, since the reactions for which they are responsible form an important part of the general pattern of soil behavior.

CALCIUM AND MAGNESIUM SULFATE

In a neutral or near neutral mineral soil the sulfate ion is most commonly associated with calcium or, to a lesser degree, with magnesium. The pH of an aqueous solution of calcium sulfate is 7.5 to 7.8, that of a magnesium sulfate solution 6.6 to 7. These salts, therefore, have no unfavorable influence on the soil pH, nor do they have any detrimental effects on higher plants, even if they should be present in rather large amounts.

DOUBLE DECOMPOSITION OF CALCIUM SULFATE WITH SODIUM CARBONATE

In truly alkaline soils, above pH 7.5 and 8, the alkalies are usually present as carbonates, and one of the most common of these is sodium carbonate. If calcium sulfate (gypsum) is added to such a soil, a double decomposition (see page 161) takes place, which is rather significant and which may be expressed by the following equation:

$$\underset{\substack{\textit{sodium}\\ \textit{carbonate}}}{Na_2CO_3} + \underset{\substack{\textit{calcium}\\ \textit{sulfate}}}{CaSO_4} = \underset{\substack{\textit{sodium}\\ \textit{sulfate}}}{Na_2SO_4} + \underset{\substack{\textit{calcium}\\ \textit{carbonate}}}{CaCO_3}$$

Since calcium carbonate is difficultly soluble and is much less alkaline than the readily soluble sodium carbonate, and the almost equally soluble sodium sulfate is practically neutral in reaction (pH 7 to 7.2), this results in lowering the pH value of an alkaline soil, though usually not to a very great extent. This process is sometimes employed in efforts to improve highly alkaline soils. (See also page 416.)

CALCIUM SULFATE AND CALCIUM HYDROXIDE

It is important that the calcium compound used for this purpose be calcium sulfate (gypsum), not calcium hydroxide (hydrated lime). The latter, unfortunately, is quite frequently recommended for the improvement of heavy clay soils which frequently are alkaline. Such applications of hydrated lime, without first making sure of the pH value of the soil, can actually have disastrous consequences, because they are likely to produce an effect exactly opposite to what was wanted. (See pages 315 and 408.)

ALUMINUM SULFATE, IRON SULFATE, AND MANGANESE SULFATE

In acid soils below pH 6, the SO_4 ion is most frequently associated with iron and with aluminum or, to a lesser degree, with manganese, forming sulfates. These sulfates are readily soluble at low pH levels and, if present in surplus amounts, may have serious detrimental effects on certain higher plants. The most dangerous one is aluminum sulfate, since aluminum itself is toxic to plants when it is freely available.

Production of Sulfuric Acid in Acid Soils

Free sulfuric acid is produced when any of the above-mentioned sulfates are dissolved in water at low pH levels. This is due to a hydrolytic process (see page 156) which may be explained by means of the following equation:

$$\underset{\substack{\textit{aluminum}\\\textit{sulfate}}}{Al_2(SO_4)_3} + \underset{\textit{water}}{2H_2O} = \underset{\substack{\textit{basic aluminum}\\\textit{sulfate}}}{2Al(SO_4)OH} + \underset{\substack{\textit{sulfuric}\\\textit{acid}}}{H_2SO_4}$$

In the presence of a large surplus of water, the following reaction may take place:

$$\underset{\substack{\textit{aluminum}\\\textit{sulfate}}}{Al_2(SO_4)_3} + \underset{\textit{water}}{6H_2O} \rightleftharpoons \underset{\substack{\textit{aluminum}\\\textit{hydroxide}\\\textit{insoluble}}}{2Al(OH)_3} + \underset{\substack{\textit{sulfuric}\\\textit{acid}}}{3H_2SO_4}$$

Although the sulfuric acid is likely to cause injury to higher plants, still more dangerous is the fact that the aluminum hydroxide which has been formed is stable only at a rather limited pH level, between 6 and 7. Below 6 it re-forms the readily soluble aluminum sulfate by reacting with other sulfates, and above 7 it reacts with sodium hydroxide to form the equally soluble sodium aluminate. In either case, free Al^{+++} ions are likely to be present in the soil solution in amounts large enough to be inimical to plant growth.

Aluminum Sulfate for Acidification of Alkaline Soils

The narrow limits of the pH range at which the evolved aluminum hydroxide remains insoluble constitute a grave danger in any attempt to acidify an alkaline soil through the application of aluminum sulfate. If large amounts are incorporated in one move, the soil pH value may very well drop below the safety limit. Even when this happens only in spots and no more than temporarily, the damage to the plants caused by the sulfuric acid and the free aluminum ions, which are bound to develop, will be equally severe. In any such procedure it is necessary, therefore, to watch the pH value of the soil very carefully by means of repeated tests, and the aluminum sulfate must be applied gradually and only in the form of an aqueous solution, not as dry powder.

ADDITION OF SULFUR TO SOIL

With Fertilizers

Many commonly used fertilizers, such as superphosphate, ammonium sulfate, and potassium sulfate, contain sulfur, so that whenever they are applied sulfur is added to the soil. The average topsoil contains rather large amounts of mineralized sulfur, and all organic matter added to soil for the purpose of increasing humus content likewise contains sulfur.

By Rain Water

In addition, sulfur enters the soil also with rain water which absorbs it from the air where it is present as sulfur dioxide (SO_2). In regions where fog is a frequent occurrence, as on the American west coast, the sulfur dioxide discharged from the chimneys of various industrial plants oxidizes to sulfuric acid, resulting in a poisonous smog which irritates the eyes and throat. The sulfur dioxide of the air represents merely a pollution, and, in consequence, the amounts of sulfur which rain water may add to the soil vary considerably from region to region. In the country it is likely to be very little (2 to 3 lb/acre/year), but in the vicinity of industrial centers or of ore smelters the amount may be quite high (100 lb/acre/year or even more).

Amount Needed

Since the average crop does not withdraw very large amounts of sulfur from the soil (approximately 56 lb/acre/year) sulfur deficiency, as far as plant nutrition is concerned, is not a common occurrence, though it does happen occasionally. Sulfur application is more likely to be required for the sake of some of the other important functions of sulfur than for the purpose of supplementing sulfur nutrition. It is definitely advisable, though, to establish clearly in advance what is one's object and what are the likely consequences before applying sulfur to the soil.

23. THE STORY OF IRON

NATURAL IRON COMPOUNDS

Elemental iron is found on earth only occasionally in the form of meteoric rocks. In combination with other elements, however, iron forms a common component of numerous minerals. These minerals either are included in various types of igneous, sedimentary, or metamorphic rocks (see page 152) or occur in more or less extensive separate deposits. The most important of the latter are the oxides, such as hematite (Fe_3O_3) and magnetite (Fe_3O_4); the carbonate, siderite ($FeCO_3$); and the sulfide, pyrite (FeS_2).

Hematite

Hematite deposits such as those in the Lake Superior region and Brazil are believed to have developed through weathering and erosion of huge beds of iron carbonate and silicate which, as the consequence of bacterial activity, were deposited at the bottom of extensive inland seas. In some cases (in Cuba, for instance) hematite as well as limonite deposits (see page 157) appear to have developed from rocks which originally contained only little iron. It must be assumed that, during the weathering process, the insoluble iron remained behind and accumulated, and the various more soluble impurities were leached away.

Magnetite

Magnetite (in the Adirondacks, Canada, Sweden, etc.) is believed to have segregated from volcanic magmata during the cooling process.

Siderite

Siderite ore (iron carbonate) developed from sedimentary deposits at the bottom of inland seas and also under the shallow waters of marshes, lakes, and even rivers. Through oxidation and hydration, siderite turns into hematite and limonite. In America, siderite ores are less important than hematite and limonite, but European deposits, especially in England, France, Germany, and Spain, are of great importance and value.

Pyrite

Pyrite (iron sulfide, commonly called *fool's gold*) is a frequent component of igneous as well as of sedimentary and metamorphic rocks. Since it oxidizes very readily, with the formation of sulfurous or sulfuric acid, it serves as an active agent in the decomposition of the rocks which contain it. It is not an economic iron ore because of the difficulty of removing the sulfur, but it is mined extensively (California, Virginia, Spain) for the production of sulfuric acid.

Silicate Minerals

Various silicate minerals—especially olivine—contain iron, usually coupled with magnesium. During the weathering of such minerals, the iron is freed and enters the soil or is left over and accumulates as an end product of weathering.

IMPORTANCE OF IRON TO PLANTS

Organic Iron Compounds

Since iron is contained in all plant and animal bodies, it is always present in the soil also in various complex organic compounds which, through decomposition by means of biological processes, are gradually converted into available or unavailable inorganic forms.

Iron as a Plant Nutrient

Experiments carried out in many countries have given irrefutable proof that iron is an essential plant nutrient. In 1892 Molisch showed that, though plants contain only relatively small amounts of iron, iron deficiency of the soil causes chlorosis—gradually increasing yellow discoloration of the leaves. Addition of iron to the soil, or even application of a dilute iron solution directly to the leaves, quickly restores the chlorophyll to health, and the leaves turn green again. Willstaetter demonstrated that chlorophyll does not contain iron, and it is assumed that the main function of iron in the plant is to assist somehow in the photosynthetic action of chlorophyll—perhaps as a catalyst. Whatever role iron actually plays in the life of a plant, there is no doubt that it is indispensable for plant health.

Ferrous and Ferric Oxide

The most important fact concerning the behavior of iron in the soil is the ability of this element to form several distinct states of oxidation. Two of these, which commonly are present in the soil and usually occur together, are of interest. These are the ferrous oxide (FeO), in which iron is bivalent, and ferric oxide (Fe_2O_3), in which iron is trivalent. Their differences in oxygen content—ferrous oxide, as the formula shows, is poorer in oxygen—are very significant, as will be shown presently. The proportion in which these two types of iron oxide occur in any given soil has an important bearing on general soil condition and on plant nutrition. (See page 160.)

Influence of pH on Iron Availability

From pH 3 to slightly above pH 5, ferric iron is soluble and, therefore, is available in the soil; up to neutral or slightly above, ferrous iron takes over; and up to approximately pH 8, ferric and ferrous humate are still soluble. The two humates, which are readily soluble at nearly all pH levels (probably even above pH 8), are always present in small but sufficient amounts wherever humus is present. True iron deficiency, therefore, is rare in nature and is likely to develop only under artificial conditions through unskilled interference with the balance of nature, or where sodium is present, causing a pH above 8. The physiological deficiency of iron which occurs in highly calcareous soils and which actually is much more common than a true deficiency is discussed on page 245. That a high concentration of soluble ferric iron produces toxic effects on most plants has been mentioned previously.

BOG IRON ORE

Water which drains away from soils with a high content of ferrous carbonate—for instance, from swampy woods—provides a favorable medium for the development of various iron bacteria. These bacteria have the ability to oxidize ferrous to ferric iron and, since the latter is precipitated, this bacterial activity leads to the formation of deposits of bog iron ore [$Fe_2(OH)_4$]. Chemically, this is the oxidation and hydrolysis of soluble ferrous carbonate into insoluble ferric hydroxide, according to the following equations:

$$\underset{\substack{\textit{ferrous}\\ \textit{carbonate}}}{4FeCO_3} + \underset{\textit{water}}{2H_2O} + \underset{\textit{oxygen}}{O_2} = \underset{\substack{\textit{basic ferric}\\ \textit{carbonate}}}{4Fe(OH)CO_3}$$

Ferric carbonates, being very unstable in the presence of water, are quickly converted through hydrolysis into water-insoluble ferric hydroxides, as follows:

$$\underset{\substack{\textit{basic ferric}\\ \textit{carbonate}}}{Fe(OH)CO_3} + \underset{\textit{water}}{2H_2O} = \underset{\substack{\textit{ferric}\\ \textit{hydroxide}}}{Fe(OH)_3} + \underset{\substack{\textit{carbonic}\\ \textit{acid}}}{H_2CO_3}$$

This may happen chemically when virgin soils with a dense sod and grass cover are plowed, resulting in temporary lowering of iron availability.

Not infrequently, deposits of bog iron ore become extensive enough for commercial exploitation. The same bacteria (*Gallionella, Leptothrix, Cladothrix,* and others), which are responsible for the formation of bog iron ore in swamps, occasionally cause complete blockage of water pipes leading from springs or wells. (See page 53.)

HARDPAN

Under certain conditions, especially when an acid layer of raw humus forms over sand while the water table is low, the precipitated iron hydroxide together with various colloidal substances may, after filtering through the sand, coagulate suddenly at a lower level, cementing the sand together. This results in the formation of a hard water-impermeable layer, a so-called *hardpan,* which even tree roots cannot penetrate. It is the iron hydroxide which is responsible for this and which gives to the hardpan its characteristic reddish-brown color.

Such a condition, naturally, is very unfavorable for plant growth, since it interferes with drainage and with soil aeration. Trees are likely to become stunted, and agricultural crops are sure to give poor results. A considerable improvement can frequently be achieved by breaking the hardpan with regularly spaced low charges of dynamite placed in such a manner that they work downward instead of upward. Wherever natural soil conditions seem to favor the development of hardpan or where cultural results give reason to suspect its existence, an investigation of subsoil conditions is recommended. Though it may seem strange to have to use dynamite in a sandy soil, this is the best procedure.

24. THE STORY OF CARBON

Because plants can absorb carbon only in gaseous form, as carbon dioxide, and only through their leaves directly from the air, this element occupies an altogether unique position in nature. Obviously, it is not possible to feed it to plants by adding carbon compounds to the soil as fertilizer, in the manner practiced with all other required elements. Yet carbon is absolutely essential for all life processes; neither plants nor animals can live without it. The great importance of this element makes it well worth considering in some detail how carbon moves in an endless cycle. How complete is this cycle?

THE CARBON CYCLE

The carbon absorbed by the plants from the air is converted through photosynthesis (page 101) into carbohydrates and proteins. Animals, which cannot acquire carbon from the air, have to obtain it by using plants as food. Carnivorous animals get their carbon third hand from the herbivorous animals which they kill and consume. In the animal body, carbohydrates are the chief source of heat and energy, and the proteins, which consist of about 50 per cent carbon, make up most of the solid matter of all animal cells and tissues.

To complete its cycle the carbon, which thus has been incorporated in the animal body, has to be returned to the air. This is accomplished by means of several different processes. First of all, part of the carbohydrates consumed as food—the glycogen part—is oxidized in the animal or human body into carbon dioxide and water, with the carbon dioxide being returned to the air in breathing. Second, growth of the human or animal body does not proceed in a straight line, as a continuous process of building up, but is paralleled by a breakdown of cells which goes on simultaneously. This breakdown of cells likewise ends in the oxidation of carbon to carbon dioxide, which is exhaled.

Decomposing Organic Matter a Source of Carbon Dioxide

Naturally, only a fraction of the carbon dioxide originally absorbed by plants from the air is returned to the air through the breathing of animals; a much larger part remains locked up in the tissues of animals. In addition, of course, not all plants are consumed as food. The cycle therefore remains incomplete until the rest of the carbon which enters the soil in the form of plant residues and animal bodies is freed, so that it can return to the air. The indispensable link in this chain is provided by the soil microorganisms which decompose the organic matter and produce carbon dioxide. Since the latter is a heavy gas which does not diffuse rapidly, it remains—as long as wind does not disperse it—in the lower air layers, surrounding the plants and ready at their disposal. In fact, plants obtain most of their required supply of carbon dioxide from decomposing organic matter.[1]

Carbonates

Seemingly, this closes the cycle, but actually it does not. A considerable deficit results from the fact that carbon dioxide readily enters the molecules of numerous substances, forming carbonates, a very large number of which are known to occur in nature. Even if only one of these, the ubiquitous calcium carbonate or limestone is considered, it becomes readily evident that not all of the carbon dioxide contained in soil or water is returned to the air. Nor is the precipitation of calcium carbonate merely a historical process. It still continues and will continue in the future.

Hydrocarbons and Crystallized Pure Carbon

Other large amounts of carbon compounds are withdrawn from the cycle in organic form as peat deposits. Still larger ones, likewise of organic origin, the vast deposits of coal, petroleum, bitumen (asphalt), and natural gas—so-called hydrocarbons—represent the air deficit of carbon dioxide of long-bygone ages. Millions of years ago these organic

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[1] It has been calculated that, under favorable moisture and temperature conditions, 1 kg of soil may in 24 hr give off 5 to 30 mg of carbon as carbon dioxide. At an average of 10 mg/day, an acre of soil containing 10,000 kg of carbon will, during the four warmest months of the year, give off 1,000 kg of carbon in the form of carbon dioxide. (Waksman, S. A., "Soil Microbiology," p. 98, New York, John Wiley & Sons, Inc., 1952.)

deposits became deeply buried and, under the influence of heat and pressure, were transformed into their present state. Under very special conditions, even pure elemental carbon developed—likewise originally from organic matter—and crystallized into diamonds or into graphite. These two minerals are chemically identical and differ only physically. The color is no criterion, since diamonds may be black (carbonado). Graphite, from which pencils are made, but which is used for various other purposes also, is generally considered to be the extreme end product of the same natural process which resulted in the formation of coal. In this case the volatile hydrocarbons have been driven off by heat and pressure, leaving pure carbon behind. Graphite is mined in various parts of the world (Texas, Canada, Ceylon, and Madagascar), and large amounts of it are now produced artificially from anthracite coal in electric furnaces. In nature, graphite is a very common component of igneous as well as of metamorphic rocks (gneiss, schist, and marble), which contain it either as separate flakes or in irregular masses.

Air Content of Carbon Dioxide

It must be assumed that, during the so-called Carboniferous period, the air had a considerably higher average content of carbon dioxide than it has at present. The extraordinarily luxuriant development of the many types of plants which characterized this period, and which resulted in the above-mentioned carbon deposits, would not have been possible otherwise. Much of this carbon which has so long been withheld from the air is now being returned to it as carbon dioxide by the burning of huge amounts of coal, gas, and petroleum as fuel. In addition, immense quantities of carbon dioxide gas are, in some localities, emitted from the ground or from mineral springs and wells.

Completeness or Incompleteness of the Carbon Cycle

It is clear that the carbon cycle does not run smoothly, because the amounts of this element which become trapped in the soil and in the rocks—sometimes for thousands and even for millions of years—are very large. The carbon incorporated in carbonates remains locked away until the rocks containing it weather and disintegrate. Yet, over a long enough period of time, most of the carbon undoubtedly does return to the cycle in various ways. This much is sure: enough of it circulates to maintain a surprisingly uniform carbon dioxide content of the air (approximately 0.3 per cent by volume) all over the world. Only over the southern Atlantic Ocean is the carbon dioxide content of the air, for some as yet not fully explained reason, persistently somewhat higher than average. Therefore, the carbon cycle very evidently is reasonably complete, though it is impossible to tell with certainty how the balance is being preserved.

MEETING THE CARBON DIOXIDE NEEDS OF PLANTS

As shown above, the carbon dioxide supply of the air is usually sufficient for the needs of the plants. On the other hand, the incorporation in the soil of organic matter assumes additional importance, beyond the other benefits obtained, because of the carbon dioxide produced during its decomposition. Windbreaks (page 185) aid very materially in maintaining a high air content of carbon dioxide around commercial crops. The speedy and healthy development of plants raised in a properly prepared old-fashioned hotbed, heated with horse manure, can undoubtedly be traced, at least in part, to the confinement of the freely developing carbon dioxide.

AMORPHOUS AND ACTIVATED CARBON

A few other forms of carbon may be mentioned in conclusion. Incomplete combustion (when insufficient oxygen is present) of carbon compounds leads to the formation of amorphous carbon, such as soot, lampblack, charcoal, and coke. This process is employed in the artificial production of very pure carbon by burning chemically pure organic substances, such as sugar. Under certain conditions, which must be carefully controlled, carbon prepared in this manner acquires the ability to hold on its surface (to adsorb) certain impurities contained in various gases or liquids. Such carbon is called *activated carbon* or *activated charcoal* and is employed in the purification of many products and of drinking water.

CARBON MONOXIDE AND CARBON DIOXIDE AS POISONS

Carbon monoxide (CO) is produced together with carbon dioxide when carbon is burned with a limited supply of oxygen. It is emitted from the exhausts of all internal-combustion engines. This is a highly dangerous gas, which acts as a blood poison, and which, when breathed even at very low concentration, kills by destroying the ability of the hemoglobin of the blood to carry oxygen.

25. THE AVAILABILITY OF SOIL SUBSTANCES TO PLANTS

Solubility Decisive for Availability

The solubility of a substance, as previously explained, is the first requirement for availability to plants, because, in the act of dissolving, the substance dissociates into ions (page 30). It is these ions which the plant is able to absorb. Water-insoluble substances do not dissociate into ions and, therefore, are not available to plants. Since plants are able to absorb ions not only from the soil solution, where they are subject to loss in drainage, but also through contact and exchange directly from the soil colloids which hold them adsorbed (see page 76), they are assured of a steady supply. They would be at a serious disadvantage if they had to depend solely on the fluctuating amounts present in the soil solution.

Total Amounts Available

For a computation of the total amounts of the various substances which are available to plants in the soil, both those present in the soil solution and those held adsorbed by the soil colloids but available through exchange (the exchangeable amounts) must be taken into account. This fact, indeed, serves as the basis for all efforts to establish available amounts through soil analysis.

Importance of Proper Nutritional Balance

To appreciate what is involved in providing plants with everything they need in a properly balanced nutrition, one must never lose sight of the fact that plants are living organisms and not merely systems of chemical compounds. Thus they, like other organisms including man, are likely to "indulge" in the wrong kind of food when it is too freely available. This may result in their being unable to utilize certain other elements needed for their health and growth, in spite of the fact that the latter are present in the soil in soluble form and in sufficient amounts. Actually, there is considerable similarity between this phenomenon in plant life and the fact that in the diet of human beings certain foods, which by themselves are perfectly good and nourishing, cannot be properly digested when they are eaten together with certain others.

Interference of Potassium, Calcium, and Magnesium in Utilization of Other Elements

The most pronounced effect on the ability of plants to absorb other nutrients is exerted by the three main bases; viz., potassium, calcium, and magnesium. Either one of the first two, when amply available in the soil, is likely to accumulate in the upper parts of the plants in larger amounts than required. This has a depressing effect on the absorption of other nutrient elements. For a proper balance the latter actually are now needed in correspondingly larger amounts, so that the shortage is intensified. The result is likely to be a so-called "physiological deficiency" —most commonly in one or several of the minor elements. This means that the plants develop the symptoms typical for deficiency of some element, in spite of the fact that soil analysis shows sufficient amounts of the latter to be present in available form.

Calcium-Induced Physiological Iron and Manganese Deficiency

Rather commonly involved in this phenomenon are iron[1] and manganese in highly calcareous soils with a pH value above 7 5. Under such conditions the surplus calcium is the cause. Proof that this is not merely a case of iron and manganese being converted into insoluble forms in the soil is supplied not only by soil analysis but by the fact that the roots of the plants do absorb both elements and that only the movement of the elements within the plant is impeded by their being precipitated within the cells. It is evident that the application of iron or manganese sulfate to the soil is quite useless, as long as there is no true deficiency, and in most such instances this will produce no effect at all. One might apply either iron or manganese sulfate or both as a spray to the plants

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[1] In certain acid soils with a high magnesium content, physiological iron deficiency is likely to develop through the availability of surplus amounts of magnesium. It seems only logical to assume that the reverse, viz., magnesium deficiency caused by surplus amounts of available iron, could happen in the same manner, depending upon which element happens to be present in larger amounts, but this does not appear to have been observed.

themselves, which would result in turning the yellowed leaves green, but this would be only a temporary expedient, providing quick relief but without lasting effect.

Remedial Measures

The solution to this problem consists in the application of ammonium sulfate which will do several things. First, it will depress the dissociation of calcium carbonate, therewith rendering it less active, though it increases its solubility. Second, it will convert the insoluble hydroxides of iron and manganese—in which form both of these elements have been precipitated in the plant cells—into the readily soluble sulfates. Both then will be enabled to ascend to the leaves where they are needed. The ammonium hydroxide, which results from the same reaction, is soluble, and, since the soil content of ammonium is usually very low anyhow under such conditions, the addition of ammonium in itself will prove beneficial. To what extent ammonium, as such, may be involved in enabling plants to utilize certain minor elements, such as iron and manganese, does not appear to have been investigated and unquestionably deserves further study. The chances are that ammonium plays a much more important role in the soil-plant relationship than is generally realized.

Physiological zinc, copper, and boron deficiencies may develop from the same causes and should respond to the same treatment.

Potassium Deficiency

The content of a natural soil in available potassium is much more likely to be low than high. Since potassium frequently receives considerably less attention in fertilizer application than do phosphorus and nitrogen, a potassium deficiency, in relation to the other elements, is much more common than is a potassium surplus.

A soil content low in available potassium is particularly unfavorable when readily available nitrogen in any form is applied, because potassium appears to exert a beneficial controlling influence on the amount of nitrogen a plant can absorb. In the absence of balancing amounts of available potassium, plants are likely to absorb more nitrogen than is good for them, which results in sappy, disease-susceptible growth[2] and in little or late production of flowers. This unfavorable effect, which is quite common in the garden culture of flowers, is prevented when the supplies of the other elements and, most of all, of potassium are main-

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[2] Stalk rot of corn, for instance, has been found to be favored by nitrogen applications when the potassium level is low.

tained at a proportionate level. A low potassium level, furthermore, appears to render inefficient the plant's absorption and utilization of copper, especially when conditions are such that calcium and magnesium are readily available. This may happen when the pH value of a more or less acid soil is raised to near neutral through the application of dolomitic limestone, without paying attention to the soil potassium level. Physiological copper deficiency then may develop.

Potassium Surplus

An unfavorably high content in potassium is most likely to develop in greenhouse soils which have been fertilized repeatedly and indiscriminately without soil analysis. Such a high potassium level—over 600 or 700 lb/acre of potassium—will interfere most of all with the absorption of magnesium and may cause physiological magnesium deficiency. The absorption and utilization of calcium, iron, and manganese may be interfered with also.

The application—and especially the repeated application—of large amounts of potassium salts in the field is likely to result in magnesium deficiency of the plants, even when sufficient magnesium is present in the soil. This has been observed particularly in apple orchards, with certain varieties of apples appearing to be more susceptible than others to this type of injury. Since plants which lack magnesium show a higher rate of transpiration than those which contain potassium and magnesium in proper proportion, the former are more likely to suffer in a spell of hot weather. In a hot dry summer, magnesium deficiency symptoms are, therefore, more likely to become prominent than in a cooler, wetter summer. It is evident that, in the field as well as the greenhouse, one must be careful with the one-sided application of a potassium fertilizer; application of the double salt potassium-magnesium sulfate is much safer than potassium sulfate when large amounts of potassium fertilizer are required to establish a proper balance.

Phosphorus Surplus

Phosphate (PO_4) likewise accumulates in the soil when surplus amounts are applied repeatedly without control through analysis. This also is most likely to happen under greenhouse conditions, and a high phosphorus level—over 2,000 lb/acre of phosphorus (as P) have occasionally been found in greenhouse soils—is particularly objectionable when the soil nitrogen content is low. A high phosphate level, furthermore, lowers the solubility and thus the availability of iron. There is reason to suspect that this type of unbalance increases the susceptibility of greenhouse carnations to bacterial wilt. Such conditions are seldom found in the field.

In the forcing of hydrangeas (hortensia, four season) it has been observed that the phosphorus level has an indirect influence on flower coloring. It appears that phosphorus interferes with the absorption of aluminum or—what is most likely—with the movement of the latter within the plant. Probably aluminum is precipitated, at least in part, within the cells as insoluble aluminum phosphate. Since aluminum is required to produce a good blue color in hydrangeas, the phosphorus content of the potting soil must be kept relatively low (approximately 50 lb/acre of phosphorus), and no phosphate must be applied during forcing if blue flowers are wanted. To obtain a good, clear, pink flower color, on the other hand, superphosphate should be applied even during the forcing period. A high phosphate level in the potting soil of hydrangeas which are treated with aluminum sulfate to produce blue flowers will result in dirty purple colors.

Molybdenum Deficiency

Physiological molybdenum deficiency occurs rather commonly in acid, peaty or sandy soils which contain surplus amounts of available manganese and of various sulfates. Both of the latter interfere with the molybdenum uptake of plants. Liming helps very appreciably under such conditions, and no sulfates, such as potassium sulfate or superphosphate (which contains 50 per cent gypsum, calcium sulfate), should be applied. Since soils of this type frequently are deficient in phosphorus, treble superphosphate may be used, or potassium phosphate may be employed to supply both potassium and phosphorus. There is rather clear evidence that phosphates assist in the molybdenum absorption of plants, and a satisfactory soil phosphate level therefore is particularly important with soils of low molybdenum content.

A high nitrogen level also interferes with molybdenum assimilation, and, especially, the application of large amounts of nitrate aggravates whiptail symptoms in cauliflower.[3]

Phosphate Absorption Controlled by Magnesium

Magnesium appears to be involved in the uptake of phosphate by plants,[4] the latter being inefficient when soil magnesium content is low.

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[3] Stout, P. R., Meagher, W. R., Pearson, G. A., and Johnson, C. M., *Plant and Soil,* **3,** 51 (1951); Mulder, E. G., *Plant and Soil,* **5,** 368 (1954).

[4] Mulder, D., in *Plant and Soil,* **4,** 107 (1952).

In consequence, it is advisable to check on soil magnesium content when plant phosphate utilization is poor in spite of the presence of sufficient amounts of available phosphate. Magnesium fertilizer rather than more phosphate should be applied when soil analysis shows a low soil content in available magnesium.

There still is a good deal more to be learned concerning the interdependent action of the various plant nutrients. The above-cited examples, however, may suffice to emphasize the importance of a proper nutrient balance as well as to stress the fact that the processes involved are as much biological as they are chemical. (See page 314 for the cause of true deficiencies.)

PART V

Manures, Composts, and Fertilizers

INTRODUCTION

The use of various fertilizer materials, such as manure, bones, wood ashes, fish, and even limestone, is quite as old as true agriculture itself, though the reasons why these substances produced the effect they did, were, of course, not understood. Even the Indians of North America were in the habit of burying a fish in each hill of earth in which they sowed their corn, and they did this long before they came into contact with white men. The South American Indians had discovered, in the same empirical manner, that the addition of guano increased the yield of their fields.

Strange to say, vast numbers of farmers all over the world still proceed in exactly the same manner, guided by feel or instinct, as their forebears did a thousand or two thousand years ago. Nearly each one has his own preferred type of fertilizer material on which he depends, yet does not know the underlying reasons for the results he obtains. In consequence, he is unable to judge whether some other fertilizer material might not be much more economical for him to use and at the same time would, perhaps, give him still higher yields.

The old and still heatedly continuing controversy over the use of either organic or inorganic fertilizer materials, or both, rests on the same basis of lack of insight and failure to understand the actions of the various substances. In weighing pro and con, one should never lose sight of the following fundamental facts:

(1) What plants extract from the soil and use as nutrients are the ions of the various substances (page 30), and it does not make any difference whatsoever whether these ions, such as the phosphate ions of phosphorus, the sulfate ion of sulfur, or the ammonium ion of ammonia, originated in the soil through biological decomposition of organic substances or came from an artificially produced salt which was added to the soil. The ions are absolutely identical in each case, no matter what their origin.

(2) A natural or virgin soil and a cultivated soil are two very different growing media. In the former, a balance establishes itself between the nutrients which gradually become available in a natural way and

the vegetation which inhabits the soil. In other words, no more grows on such a soil than the soil can support, and the plants which settle there actually have chosen this particular soil because its natural nutrient balance suits their needs.

When such a soil is plowed and taken into cultivation, plants are forced onto it which are completely foreign to it and which have much higher nutrient requirements than the native vegetation. Besides, as has been pointed out previously, cultivation results in aeration, accelerated decomposition of organic matter, and greatly increased leaching. Since cropping unavoidably includes the final removal of a large part of the plants which were grown on a field—root crops are removed in their entirety—the cyclic return to the soil of the nutrients removed by the plants is interrupted, and the natural nutrient balance of the soil is broken. Therefore, even the richest natural soil will become gradually more and more impoverished under cultivation if fertilizers of some sort or other are not added to it regularly.

(3) Agriculture is an industry in which, as in any other industry, the cost of production must be carefully calculated in order to assure a profit.

To supply a soil with all required nutrients by adding only organic substances is definitely possible. Since all the nutrient substances which any plant requires are contained in the bodies of animals and plants, which go into the making of a good compost, a properly prepared compost can, indeed, serve all fertilizer needs. To supply large fields, however, vast amounts of compost would be required which hardly ever are available. Besides, such a procedure would be quite expensive, because the production of a really good compost requires considerable handling. In most instances, calculation will establish the fact that it is much more economical to supply, in the form of artificial fertilizers, only those substances which the soil does not contain in sufficient amounts. Soil analysis can readily establish which these are, as well as how much of each is needed. The price of the fertilizer and the sale price of the crop then make it possible to calculate how near to the maximum it is economically profitable to raise the yield.

The undisputed value of humus has been omitted here, since it has been amply covered in other parts of this book, and because humus, in itself, is not a plant nutrient. It may once more be pointed out, however, that, for best results, soil humus content must not be neglected. The amount in which it is present can, likewise, be readily determined through soil analysis; this permits the determination not only of how much should be added from year to year but also the most economical manner in which a satisfactory humus level may be maintained.

To stress what was said above about the differences between a virgin and a cultivated soil, it may also be mentioned that these have been thoroughly studied in various parts of the world; some of the most instructive results having been obtained with what is termed a *lysimeter* (from *lysis*—dissolving and *metron*—to measure). This method employs a watertight box with a perforated bottom, which encloses a definite area to a given depth. Its rim is level with the surrounding land, and the soil is placed in it in carefully cut out blocks, disturbing it as little as possible. Channels under the box lead the drainage water into receptacles, where it is gathered for analysis. The soil in the box is treated in exactly the same way as in the surrounding field and is planted with the same crop. In this manner it is possible to determine rather accurately the differences in drainage losses of nutrients between a cultivated field and, for instance, a meadow.

The following description of the various organic and inorganic fertilizers, which are at present at our disposal, will serve to evaluate their usefulness under varying conditions.

26. THE ORGANIC FERTILIZER MATERIALS

GENERAL REMARKS

Manure in all its forms, including the so-called green manure, is the oldest type of fertilizer and has been used since antiquity. Every farmer, therefore, is fully aware of its value and of the fact that it must not be wasted. The application of such materials to the soil is based mainly on the assumption that they serve to return to the soil what has been taken out of it by the crop plants. To a certain extent, this is true; as stated in the preceding introduction, if enough of such materials were available, it would be possible to satisfy with them all needs of the soil and of the plants which grow on it. The difficulty consists not only in the enormous quantities which would be required but also in the varying composition of the different materials. Even the fertilizer value of cow manure, to take only one example, varies greatly with the type of food the animals consume or even with individual cows, and there is considerable difference between the manure of different kinds of animals (horse, cow, pig, etc.), as will be shown later in this text. The same applies to different kinds of plants which may be used as green manure.

The one feature common to all natural manures and composts is that they add humus to the soil, and this fact alone will always make them indispensable. One must never forget, however, that what counts most in successful plant culture is a well-balanced nutrition, and this cannot be achieved by applying haphazardly and in random quantities whatever manure may happen to be available.

GREEN MANURE

Types of Plants Used

Green manure is fresh plant material which is plowed into the soil for the purpose of incorporating organic matter, thus supplying humus as well as the nutrients contained in the plant tissues. Such green manure may consist simply of weeds which have been allowed to take over while a field rested for several years, or grasses which previously have formed a pasture, or a leguminous hay crop, such as alfalfa or red clover, which has previously been cut for several years to serve as cattle feed. It may also consist of a crop which was planted for the sole purpose of serving as green manure, such as the most commonly used buckwheat, rye grass, vetch, or sweet clover. Soybeans, field peas, cowpeas, lespedeza, and crotalaria, as well as rye, oats, millet, sorghum, rape, and others are frequently used in the same fashion. Combinations of a leguminous with a nonleguminous plant, such as rye with vetch, oats with field peas, or oats, field peas, vetch, and rape together, are usually considered to be superior in effect to any one by itself. (See page 200.) Which type of plant or combination of plants should be chosen depends, in each case, on circumstances such as climatic and soil conditions, type of main cash crop, and price of seed required. These cannot be considered here. Neither is it possible to give directions as to the time of year at which a green manure crop should be plowed under, since this likewise depends on climatic conditions and crop sequence. For these facts, agricultural literature must be consulted.

Plants Should Be Plowed Under While Young

No matter what plant is used, best results are obtained when green manure plants are plowed under at approximately half maturity, which means before they flower or certainly not later than at the beginning of flowering. The reason is that at this stage they are still very sappy and succulent, and they decompose much more readily than later on. The temporary disappearance of available soil nitrogen, caused by the biological decomposition of all organic matter low in nitrogen content (see page 198), will thus cause the least disturbance. Plans for sowing a green manure crop must include consideration of these facts, and the date for sowing should be chosen so that the plants reach the half-maturity stage at the time of year most favorable climatically or most convenient for other reasons.

Table 26.1 shows the influence of the age of a rye plant on its chemical composition (in percentages of the dry material).

The pentosans are carbohydrates of the same chemical group as cellulose. They are singled out in the above table because they are readily determinable in all humus soils, suggesting that they are very prominent in humus formation. Together with hemicellulose, cellulose, and lignin, they form the solid cell structure and woody fiber of all plants, lignin being the least easily decomposable component. Since the last two col-

TABLE 26.1. CHEMICAL COMPOSITION OF A RYE PLANT AT DIFFERENT STAGES OF ITS DEVELOPMENT*

	10–14 in. high	Heads just beginning to form	Just before bloom	Mature plants
Soluble in cold water	34.24	22.74	18.16	9.90
Pentosans	16.60	21.18	22.71	22.90
Cellulose	18.06	26.95	30.59	36.29
Lignin	9.90	11.80	18.00	19.80
Total nitrogen	2.50	1.75	1.01	0.24
Water-soluble nitrogen	0.74	0.48	0.28	0.07

* Waksman, S. A., "Soil Microbiology," p. 103, New York, John Wiley & Sons, Inc., 1952.

umns give the analysis of stems and leaves only, and the first two columns include the whole plant, the increase in these substances just before bloom and at maturity will be even sharper than the table shows. The decrease in general water solubility of the various compounds contained in the plant tissues and, in particular, the decrease in nitrogen content are most significant and show very clearly how much is gained by plowing green manure plants under before they reach maturity. It must, of course, be remembered that it is not the actual age of the plants but their relative state of maturity which counts.

Mineral Contents of Green Plants

When trying to evaluate the benefits to be derived from green manuring, the average person will think first of all of the amounts of plant nutrient substances which are added to the soil. A glimpse of this may be obtained from the ash analysis of various plants, as given in Table 26.2.

TABLE 26.2. ASH ANALYSIS OF VARIOUS PLANTS
1,000 lb of air-dried plant material contain

		Ash contains, lb					
	Ash, lb	Phosphoric acid	Potassium	Sodium	Calcium	Magnesium	Sulfuric acid
Winter rye	39.3	2.6	10.0	1.0	2.9	0.9	1.6
Summer rye	42.0	2.0	7.5	0.6	4.0	1.2	1.5
Barley	44.9	2.0	10.0	5.0	3.3	0.9	1.8
Oats	64.5	3.5	16.0	4.0	3.8	1.2	2.0
Peas	26.3	10.0	12.5	0.2	0.9	1.3	0.8
Lupines	36.8	14.2	11.4	0.3	2.8	4.5	3.2
Red clover in flower	53.8	5.6	15.0	1.1	20.1	6.3	1.9
White clover in flower	59.1	7.8	13.1	4.1	18.4	5.8	4.5

Amounts of Nutrients Added to Soil

At first glance these amounts may appear fairly large, until one realizes that approximately 85 per cent of a plant's body consists of water and only about 15 per cent is dry substance. This means that at least 6½ times more—or, instead of 1,000 lb, slightly over 6,500 lb (over 3 tons)—of fresh plant material per acre is required to add the above amounts in pounds per acre. Since 3 tons of fresh plant material (including roots and tops) per acre represent a fairly good average green manure crop, it is evident that the amounts of nutrients actually are very small. Nitrogen does not appear in Table 26.2, since an ash analysis does not permit its determination. However, Table 26.1 makes it possible to compute that as much as 20 lb or even 25 lb of nitrogen/1,000 lb of dry plant substance (3 tons of fresh material) may be included, if rye (or rye grass or oats) is plowed under while young. This amount, however, does not add anything to the original store of soil nitrogen, if plants are plowed under where they grew, because it comes from the soil and is merely returned to it. The same applies to the other plant nutrients listed in the ash analysis. The only advantage which may be gained, as far as plant nutrients are concerned, is that some of the fertilizer, incorporated in the soil when the green manure plants were sown, will now appear in organic compounds and will gradually become available to the next crop when the green manure plants decompose. This process will save these additional nutrients from being lost in drainage and will extend their availability over a longer period. As stated elsewhere (page 200), the plowing under of a leguminous crop may, under favorable conditions, add over 100 lb of nitrogen/acre, and such nitrogen does represent an actual addition because it comes from the air. Since the favorable conditions referred to mean that the soil must have a very low natural content of nitrogen to start with, such an addition is definitely worth while.

Amounts of Humus Added to Soil

Of much greater interest is the amount of organic matter which green manure adds to the soil and which, in decomposition, will turn into humus. If approximately 3 tons/acre is taken as a norm, this corresponds to about 1,000 lb of dry substance. In decomposition this amount will be still further reduced by about half. When one takes into account that the average fertile farm soil contains from 2 to 10 per cent total organic matter, representing 40,000 to 200,000 lb/acre, it becomes apparent that the amount of organic matter added with the average green manure crop is surprisingly small.

Even when 25 tons of fresh plant material/acre are incorporated, which may be achieved when corn or sorghum is used, only about 8,000 lb of dry substance, or approximately half that much of humus, will be added to the soil. Still, such an amount would represent a worth-while addition, if not in nutrients at least in humus.

Actually, it has been found, through long-term observations under controlled conditions, that one green manure crop alone can do no more than assist in maintaining a satisfactory humus level. If only a short-term culture of some green manure plant is used from time to time as the sole means of replenishing soil organic matter, the total humus content of the soil slowly but steadily declines. To supply the quantities required, a succession of several green manure crops, extending at least over 1 whole year or even over 2 years, would be necessary.

Other Benefits of Green Manure

For a complete picture of the effects produced by plowing under a green manure crop, the various other benefits must also be considered. One of the most important of these is the development of large amounts of carbon dioxide (CO_2), the end product of energy utilization by the microorganisms. This not only serves to enrich the air over the soil surface, playing a vital role in photosynthesis, but, as carbonic acid, its action in the soil is added to that of other organic acids developing during the same decomposition processes. The marked but gradual increase in solubility and, therewith, availability of the various nutrient soil minerals results in a definite boost of plant growth.

Not negligible either is the stimulation of the soil microorganisms, which is produced through the addition of the readily available carbon contained in fresh plant material, and which results in speeding up the production of ammonium and nitrate. Even peat soils are improved by being made more active through the incorporation of a green manure crop.

PRACTICAL APPLICATIONS

In evaluating for practical application what has been said so far, the following conclusions may be drawn.

Pasture or Hay Crop. The greatest benefit to the soil, as well as the greatest economic gain, usually results from the incorporation of green manure when the plants have first served for several years as a hay crop or pasture, provided that the plowing takes place at the time the plants are in best condition for quick decomposition. Addition of inorganic fertilizer at the time of plowing is highly recommended.

Green Manure Under a Grain Crop. Sowing a green manure crop, preferably a low-growing legume, between the rows of a grain crop at the time of last cultivation is another good procedure, especially under climatic conditions which make soil protection during fall and winter necessary. The green manure crop then is left on the field as a soil cover, after the grain is harvested, and is plowed under in spring or early summer. The double purpose of the green manure crop thus turns the expense for seeds and sowing into a profit.

Improvement of Sandy Soils with Short-Term Green Manure Crops. Short-term green manure plants, such as buckwheat or vetch, are particularly worth while when a soil which contains very little organic matter (for instance, a very sandy soil) is being taken into cultivation. Green manure, in such a case, will often be the cheapest way of adding badly needed organic matter, and the expense will be made up by saving on inorganic fertilizer which will have to be added anyhow. The saving will not result from the nutrients contained in the green plants but from the fact that the organic matter will adsorb the inorganic fertilizers and thus will prevent the latter from leaching out, which otherwise they would do very quickly. Several green manure crops in succession, which, with the addition of inorganic fertilizers, are always plowed under before they commence to flower, will produce the best results. This procedure is the quickest way of restoring worn-out fields which have been impoverished through continuous one-crop culture. The economic aspect of such a procedure, as compared with a long-term leguminous hay crop or with the establishment of a pasture for several years, must, of course, be considered. The choice must depend on circumstances.

Clay Soil and Green Manure. The use of short-term green manure plants is very helpful also in the conditioning of heavy clay soils, for instance when subsoil clay has been spread over a property and a lawn is to be established on the area. The previously given details will readily explain why such treatment cannot fail to be beneficial. Addition of sand as well as inorganic fertilizer to the clay, before the green manure crop is sown, is usually most effective.

Shallow Plowing Essential. Best results are obtained with all green manure crops when they are plowed under as shallowly as possible. Deep plowing will greatly delay decomposition and will result in the loss of one of the greatest benefits, viz., soil protection.

Protective Mulch Obtained by Disking. It has been found that the mere disking over of grain stubble in the fall which, contrary to plowing, leaves most of the plant residues on the surface, produces a highly protective mulch. Any green manure crop may be disked in this fashion and plowed under shallowly later, when the field is prepared for the sowing of the next crop. Inorganic fertilizer then should be applied at the time of plowing. In general, it is advisable to wait 2 to 3 weeks after incorporation of a green manure crop, even when inorganic fertilizer has been added at that time, before sowing the next crop.

At which season—whether in fall, winter, spring, or early summer—a protective mulch will serve best depends upon the time of year at which heavy rains are most likely to cause damage. This differs widely in different localities, and each farmer must make his own decision.

SEAWEED

A special type of green manure is seaweed. This is commonly employed for fertilizer purposes along the seacoasts, where large amounts of it can readily be gathered in the spring. It decomposes rather quickly, since it contains no fiber, and should be plowed under without delay. To compost seaweed by itself is not feasible, since it turns into a jellylike mass which defies handling, but it may be added to a compost pile containing other organic matter.

Its composition when fresh is approximately as follows: water, 70 to 80 per cent; organic matter, 13 to 25 per cent; nitrogen, 0.3 to 1.0 per cent; potassium (K_2O), 0.8 to 1.8 per cent; phosphorus (P_2O_5), 0.02 to 0.17 per cent.

This means that, at an average, it contains as much nitrogen as stable manure, and may contain twice as much. Its potassium content is comparatively high, and phosphate is very low.

As much as 30 tons of seaweed/acre, or even more, are sometimes applied.[1]

FARM MANURE

Availability of Farm Manure

The value of farm manure as an aid in the maintenance of soil fertility is so well established and so generally recognized that it seems like needless repetition to say that manure must be used wherever it is

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[1] A rather interesting proposal by the Maritime Regional Laboratory at Halifax, Nova Scotia (Annual Report 1953), recommends drying seaweed and grinding it into a meal. In this form it is easily transportable and may be used either as a combined soil conditioner and fertilizer or as a food supplement for poultry and hogs. Seaweeds contain carotene as well as thiamine (vitamin B_1), riboflavin (vitamin B_2), and cobalamine (vitamin B_{12}). Vitamin C is usually present also.

available. Farm manure, however, is not readily available everywhere. The replacement of horses by motors, which is becoming ever more general, has resulted, for instance, in placing manure almost completely out of the reach of city gardeners. This situation is likely to get worse rather than better in the future. Cows are still irreplaceable, but the raising of dairy and, especially, of beef cattle is steadily becoming more concentrated in certain regions or localities. To transport manure from a region with surplus to one where it is no longer produced in sufficient quantities need hardly be considered because of the bulk and the expense involved.

For these reasons it is as futile as it is misleading to compute the amounts of available manure for a whole country from a census of the total number of farm animals being raised. This is frequently done, for instance, for the United States, in an attempt to show that there is ample manure for all needs if only it were used. What is the good of such a computation, as long as only a fraction of the total manure is produced where it actually can be used?

All farmers, however, even those who concentrate on the raising of grain, generally do keep at least a few cows as well as a number of pigs, and whatever manure is produced by these animals must be employed to the best advantage. In order to do so, one must have at least a general idea of the plant nutrients and other substances that a certain amount of manure is likely to add to the soil, as well as to know the basic facts influencing the effectiveness of a manure application.

The Manure Budget

For the most efficient use of limited quantities, it is advisable to work out a farm manure budget, for which one has to prepare an advance estimate of the amounts of manure likely to become available. Since such an estimate is basic for much of what follows, it may be considered first.

The amount of manure produced per animal depends on various factors, such as the age of the animal, the race or strain it represents, its health, and the type of food it receives. Estimates, therefore, can deal only with averages.

Estimate Based on Weight of Animals. In order to include animals of all ages, it is frequently suggested that computations be based on weight, and statistics have been prepared giving the amount of manure produced per 1,000 lb of animal. (See Table 26.3.)

This type of computation has the disadvantage that it assumes that the animals are kept in the stable all the year around, where all of the

TABLE 26.3. AVERAGE TOTAL AMOUNTS (SOLID PLUS LIQUID) OF MANURE PER 1,000 LB OF ANIMAL

Type of animal	Tons per year
Cow	10–14
Horse	9–10
Pig	14–16
Sheep	5–6
Chicken	4–5

manure can be recovered. With the exception of specialized dairy farms, this is rarely the case, and most farm animals spend at least part of the year outside where their manure is lost. Table 26.3, therefore, is not of very great help. Under average farm conditions the weights would largely have to be guessed, and such guesses might be completely wrong. It would be possible to compute that a milk cow, weighing 1,000 lb—which it may well do, though Jersey cows usually weigh from 100 to 200 lb less—and which is kept in the stable for 6 winter months, returning to the stable only for the night during the rest of the year, can be expected to produce 9 to 10½ tons of recoverable manure. This seems to be a rather optimistically high figure, since litter is not included. Besides, it is pretty certain that, in most instances, about half of the liquid manure will be lost in spite of absorption by the stable litter.

Estimate Based on Amount Produced by Mature Animals. Another type of statistics gives the average manure production of a mature animal in pounds per day, as shown in Table 26.4.

TABLE 26.4. MANURE PRODUCED BY A MATURE ANIMAL, POUNDS PER DAY

Type of animal	Solid	Liquid
Cow	52.0	20.0
Horse	35 5	8.0
Pig	6.0	3.5
Sheep	2.5	1.5
Chicken	0.1	

When these figures are used to compute the amount of manure produced by one milk cow which is kept in the stable for 6 months, and which, during the other 6 months, returns to the stable only for the night, one arrives, by including only half of the liquid manure produced, at the figure of approximately 8½ tons/year. This is probably fairly close to the truth.

The amount of manure to be expected from one horse is somewhat more difficult to compute, since, if it is used as a draft animal, it is likely to be in the stable only at night even during winter. The days of rest, which it spends entirely in the stable, may be approximately balanced by those it is likely to spend entirely outside during summer. On the basis of half the time spent in the stable, one horse would produce an approximate total of 4 tons of recoverable manure/year. Neither of these two figures, for one cow and one horse, includes the litter, though litter is indispensable if as much as possible of the liquid manure is to be saved. How much litter should be included in a computation of the total weight of manure as it comes out of the farmyard depends, of course, upon the amount and type of litter used, which varies greatly with individual farmers. Since only the dry weight of the litter need be considered, whereas wet manure is very heavy in comparison, it is generally assumed that approximately 300 lb of litter are included in 1 ton of farm manure. On this basis the above figures have to be raised to about 10 tons/year for one cow and 5 tons/year for one horse. These undoubtedly are fairly reasonable averages.

Acid Peat Moss as Litter

The type of litter used will have a considerable influence on the fertilizer value of the manure, though, for economic reasons, every farmer will have to use whatever material is most readily and most cheaply available. Straw, which is most commonly employed, is one of the least desirable materials as far as the quality of the resulting manure is concerned; sawdust is better, and an acid peat moss is best of all. The quality of these litter materials is judged mostly by their respective ability to absorb the liquid manure, and in this capacity peat moss excels all others. Besides, the free humic acid contained in acid peat moss is able to tie up chemically the highly volatile and easily lost ammonia, which adds appreciably to the potency of the resulting manure. The relative sterility of peat moss must be considered as an additional asset, especially with stabled milk cows, where stray bacteria of any kind are most undesirable. In the interest of obtaining a high-value manure, peat moss, where it is easily and cheaply available, should be used in preference to straw or any other material. What other use may be made of surplus straw of different types will be discussed under compost (page 277).

Plant Nutrient Content of Manure

The main fertilizer value of manure consists, as is generally realized, in its nitrogen content, but other substances serving as plant nutrients are present also. For balanced plant nutrition, information on the relative amounts of the various substances which are added to the soil when manure is plowed under is required. Table 26.5 gives average values. Absolute values are as impossible to compute as are absolute amounts, because of the variations introduced by the type of food, the age and health of the animal, etc. The water content is given in percentages, the total nutrient content in pounds per ton. Solid and liquid manure were analyzed together in mixture.

TABLE 26.5. AVERAGE COMPOSITION OF FRESH MANURE (SOLID AND LIQUID TOGETHER) OF PRINCIPAL FARM ANIMALS

[*Total amounts of nutrient substances (organic + inorganic), lb/ton*]

Type of animal	Water content, %	Nitrogen, N	Phosphorus, P_2O_5	Potassium, K_2O	Calcium, CaO	Magnesium, MgO	Sulfur, SO_3
Cow	80	11	4.5	12	16	4	2
Horse	60	14	5.0	15	12	8	4
Pig	85	10	7.0	8	x	x	x
Goat	70	9	6.0	18	12	x	x
Sheep	65	29	10.0	25	35	14	10
Chicken	10?	30	20.0	8	24	6	12

x is the average value not computable because of lack of a sufficient number of analyses.

Chicken Manure

Chickens frequently are only incidental on the farm, and, with the exception of specialized chicken farms, the amount of manure they produce is so small in comparison with the other animals that it may be neglected in a general computation. The same applies to goats and sheep, the latter, in particular, usually being raised separately. As can be seen, however, in Table 26.5, chicken manure is comparatively rich in phosphate, and, where plenty of it is available, it constitutes a valuable addition to the manure pile, since it helps to compensate for the lack of phosphate in the other manures. A further use for chicken manure will be mentioned later (page 274).

Mixed Farmyard Manure

Comparison with Artificial Fertilizer. Cows, horses, and pigs are kept most frequently under average conditions, and their manures are thrown together to form what is generally designated as "farmyard manure." The bulk of the manure, however, is likely to come from the cows, and average figures for content of nitrogen, phosphorus (P_2O_5), and potassium (K_2O) of a mixture of the three manures are likely to be approximately 11, 5.5, and 12 lb/ton, respectively. To be on the conservative side and for ease in figuring, this is usually reduced to, respectively, 10, 5 and 10 lb/ton, which corresponds to a percentage content of 0.5, 0.25, and 0.5 per cent. These amounts are surprisingly low, which becomes most evident when one realizes that 100 lb of artificial fertilizer of the ratio 10–5–10 could supply the same quantities of these three important nutrients as could 1 ton of manure.

Other Valuable Components. Such a comparison is not entirely fair, since farmyard manure contains various other valuable components, including growth-promoting substances such as creatine, auxins, and beta-indolacetic acid, and the value of these must not be underestimated. Most important, farmyard manure represents organic matter in one of its most readily usable forms which, if supplied in sufficient quantities, cannot fail to exert a highly beneficial influence. The action of the organic matter in the soil will be largely the same as was outlined under green manure, but, by being more immediately active, it is still more effective.

Supposed Unbalance of Farmyard Manure. The above comparison between manure and artificial fertilizer should be looked upon merely as a means of bringing the nitrogen-phosphorus-potassium content of farm manure into its true perspective. On the other hand, one should realize that the percentage content of 0.5, 0.25, and 0.5, which in ratio corresponds to 2–1–2, is quite satisfactory, especially when one considers that the phosphate contained in manure becomes and remains very readily available. Generally, superphosphate should be applied together with the manure at the rate of approximately 25 lb of superphosphate/ton of manure. Where soil phosphate content is known to be low, this will be advisable anyhow in order to maintain a proper balance. The proportionate content of phosphate of farmyard manure, however, is not unfavorably low, as is sometimes claimed. Ample manure applications over a period of years actually result in building up a soil phosphate reserve (Sweden). In addition, superphosphate will assist in conserving the elusive ammonia. The occasionally suggested amount of 40 to 50 lb of superphosphate/ton of manure is rather high, because, when 10 tons of manure are applied to the acre, this would amount to 100 lb/acre of phosphorus (P_2O_5) plus 50 lb/acre from the manure itself. Such high amounts of phosphate should be applied only when soil analysis shows a definite lack.

Advantages of Adding Superphosphate Directly to Stable Litter. It is frequently advocated that the superphosphate be added directly to the litter in the stable at the rate of 1 lb/cow/day if stabled for 24 hr. This would amount to approximately 25 lb/ton, since, on an annual basis, it would represent 274 lb/ton (according to the calculation of the 10 tons given on pages 263 and 264). This procedure has the additional advantage of ammonia conservation which results from the fact that superphosphate contains calcium sulfate to about half its weight.[2] The reaction which takes place may be expressed by the following equation:

$$\underset{\substack{\textit{superphosphate}\\\textit{(most active part)}}}{Ca(H_2PO_4)_2{+}2CaSO_4} + \underset{\substack{\textit{ammonium}\\\textit{carbonate}}}{2(NH_4)_2CO_3} =$$

$$\underset{\substack{\textit{tricalcium}\\\textit{phosphate}}}{Ca_3(PO_4)_2} + \underset{\substack{\textit{ammonium}\\\textit{sulfate}}}{2(NH_4)_2SO_4} + \underset{\textit{water}}{2H_2O} + \underset{\substack{\textit{carbon}\\\textit{dioxide}}}{2CO_2}$$

The highly unstable ammonium carbonate, which results mainly from the very rapidly proceeding decomposition of the urine, will thus be converted into the perfectly stable ammonium sulfate, producing a substantial saving of valuable ammonia. The water and carbon dioxide, which are evolved at the same time as well as later on, when the organic matter decomposes, will convert the triphosphate into the more readily soluble and, therewith, available, diphosphate. (See page 210.)

Disadvantages of Applying Gypsum to Litter. If only calcium sulfate (gypsum) is added to the litter, as is sometimes recommended, the reaction with ammonium carbonate is a much less desirable one. In this case, ammonium sulfate and calcium carbonate are evolved. But, if large amounts of carbon dioxide are developed, which is very likely to happen in the manure pile, the calcium carbonate is converted into the water-soluble bicarbonate. The latter reacts with ammonium sulfate to form calcium sulfate and free ammonia.

The action of gypsum may be expressed by the following equation:

$$\underset{\substack{\textit{ammonium}\\\textit{carbonate}}}{(NH_4)_2CO_3} + \underset{\textit{gypsum}}{CaSO_4} = \underset{\substack{\textit{ammonium}\\\textit{sulfate}}}{(NH_4)_2SO_4} + \underset{\substack{\textit{calcium}\\\textit{carbonate}}}{CaCO_3}$$

When the calcium carbonate, in the presence of surplus carbon dioxide, is converted to calcium bicarbonate, the above reaction is reversed, as follows:

$$\underset{\substack{\textit{calcium}\\\textit{bicarbonate}}}{Ca(HCO_3)_2} + \underset{\substack{\textit{ammonium}\\\textit{sulfate}}}{(NH_4)_2SO_4} = \underset{\substack{\textit{calcium}\\\textit{sulfate}}}{CaSO_4} + \underset{\substack{\textit{free}\\\textit{ammonia}}}{2NH_3} + \underset{\substack{\textit{carbon}\\\textit{dioxide}}}{2CO_2} + \underset{\textit{water}}{2H_2O}$$

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[2] To tie up all the ammonia which will be developed, would—as far as this can be calculated—require three to five times as much superphosphate. To use such large amounts might not only create a wasteful excess of phosphorus pentoxide in the soil but would be needlessly expensive also. Besides, complete ammonia conservation would necessitate thorough mixing of the superphosphate with the manure, which cannot be considered from a practical standpoint.

Thus the reversibility of the reaction with gypsum leaves the ammonia unsafe. The first outlined reaction with superphosphate is not reversible.

Conservation of Nitrogen

It is evident from all that has been said so far that, in the handling and application of manure, the greatest attention must be paid to the conservation of the elusive nitrogen, large parts of which are contained in the urine, where this element is particularly unstable. There is no doubt that the sooner manure is brought to the field after having been gathered, the more potent it is, especially as far as nitrogen is concerned, though naturally it is not possible to plow the manure in every day as it becomes available. The separate gathering and application of urine, as practiced, for instance, in certain European countries, is hardly feasible in North America, where the high cost of labor would make such a procedure uneconomical. Under average conditions, therefore, manure will unavoidably have to be stored until it can be used.

Proper Manure Storage

Various procedures for manure storage have been proposed which cannot be discussed here in detail. The principles which must be observed in order to keep losses to a minimum will suffice to enable the farmer to work out his own method. The main dangers to be guarded against are free access of the air and an oversupply of water, which latter may result from heavy rains. The air not only dries out the manure, which is not desirable, but also causes rapid oxidation in the pile, resulting in the development of considerable heat. This is highly undesirable, since it causes great loss of nitrogen.

Compacting the Manure Pile. To prevent heating, the manure pile should be packed as tightly as possible, so as to exclude air as far as this can be done. This requirement adds another black mark against straw as litter, since straw does not pack well and is full of air. Horse manure can be compacted well only when mixed with cow and pig manure.

Enclosure of Manure Pile. To prevent air from drying out the pile or from entering it from the outside, it is advisable to prepare a board enclosure, or to enclose the manure pile on three sides with concrete walls and on one side with boards. In case the litter is still partly dry when it is removed from the stable, it should be lightly sprinkled with water to aid in compacting it. Thereafter, watering of the manure pile should not be necessary if it is properly protected against drying out.

Heavy rains will, of course, result in leaching away large parts of the readily soluble contents, and protection against rain, therefore, is also required. This suggests a closed shed or a concrete room or pit adjacent to the barn with a wide door to the outside through which the manure can be removed.

Reasons Why Manure Should Be Treated with Care. All this may seem like a great deal of fuss to many farmers, who are likely to counter that their grandfathers always had open manure piles in the middle of the yard, always used straw as litter, and, though they used nothing but manure as fertilizer, had excellent crops. The differences between now and then which should be considered and which make the above precautions advisable are as follows:

(1) Mixed farming was much more common—to a large extent it still is in Europe—than it is now in North America. In consequence, much larger amounts of manure were generally available, and the losses which resulted from careless treatment of the manure were less severely felt.

(2) A well-regulated crop rotation, including a long hay fallow, was and still is generally practiced in Europe, which gives the soil a rest and prevents it from being severely depleted of humus and nutrients.

(3) Especially as far as our North American soils are concerned, they still maintained, up to 100 years ago, much of their original richness and fertility, of which they have now been robbed through continuous cropping. This means that they produced good crops not because, but in spite of, the way in which the manure was treated.

Winter and Summer Manure. The largest amounts of manure generally accumulate during winter, when the animals are kept in the stable, and it is this manure most particularly which has been considered in the recommended precautionary procedures, because this is the manure that will be available in spring. There is general agreement that spring is the most appropriate time for manure application to the fields. Manure storage during summer is much less worth while, since outside heat has, of course, the same effect as inside heat, causing large losses of nitrogen. Summer manure, therefore, is best plowed into the soil as soon as possible, or used for top-dressing where this appears desirable or, still better, employed in the composting of other organic matter.

Application of Manure to the Field

The most efficient way of applying manure as fertilizer can be deduced from the above explanations. It is evident, for instance, that the practice of taking manure to the field in winter and leaving it on top of the snow is extremely wasteful. The runoff from the melting snow will result in terrific leaching losses, and, in addition, the freezing to which the manure is thus exposed, and which is similar in effect to drying, will drive out a large part of the ammonia. When manure is brought to the field, it must be plowed in as quickly as possible in order to avoid losses. Systematic investigations have proved that a delay of even 1 or 2 days will make a big difference in the value of the manure and, therewith, in the effect it has on the crop. Evidence gathered in various countries points to the fact that manure application in rows (called bouts in England) is more efficient and effective than if it is scattered over the whole field. When manure is spread broadcast as a top-dressing, this should be done on a cool, cloudy day, preferably before a rain.

Amount of Manure to Be Applied per Acre

Not all of the 10–5–10 lb/ton, respectively, of nitrogen, phosphate, and potassium (K_2O) which were computed from the above-given analysis, will immediately be at the disposal of the plants. These are total amounts, and systematic experiments in the field tend to show that only approximately one third of the total nitrogen actually becomes available during the first year. Approximately one third is lost, and the rest becomes available during the succeeding 2 or 3 years.[3] The noticeable beneficial effects of a manure application continue for at least 3 or 4 years.

Those amounts which are, or become, available are rather perishable. This applies especially to nitrogen, but the various other contents too are likely to be converted in the soil into insoluble and, therefore, unavailable compounds if they are not used by the plants before this happens. This suggests that the application of large amounts of manure, much over 10 tons/acre, is uneconomical, and experimental evidence tends to support this deduction. Usually, it is more profitable to apply only 8 to 10 tons of manure/acre and to use inorganic fertilizers as supplements to it.

Manure as Humus

It also must be borne in mind that manure, especially when it has been properly stored over winter and therefore is partly fermented, represents humus in an exceptionally active form. Since humus is capable of adsorbing readily soluble inorganic fertilizers, holding them in readiness and preventing them from leaching away, the very presence of manure in the soil renders applications of inorganic fertilizer more effective as well as

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[3] Approximately 70 per cent of the potassium (K_2O) contained in manure becomes available during the first 2 years after application.

more economical. Actually, this is one of the most valuable gains resulting from manure application.

Frequency of Manure Application

Usually, manure is applied to a field every third or fourth year, and this, because of the residual effects mentioned above, is generally a satisfactory procedure. Only under exceptional conditions, where large amounts are available and special crops are to be raised, may annual application be considered. To which crop in a rotation manure should be applied for greatest efficiency, when the amounts available permit its use only once every few years, cannot be discussed here. It may be mentioned, however, that, because farm manure decomposes in the soil much more rapidly than green manure—provided it does not contain large amounts of straw—it is possible and advisable to sow immediately after the manure has been incorporated in the soil.

COMPOST

The word "compost" comes from the Latin word *componere,* which has given rise also to the verb: to compose—to put together. "Compost," from *compositum,* therefore, is closely related to the word composition and means originally merely a mixture of things. In practical usage the word "composting" has gradually come to mean the throwing together of various waste organic materials, so that they will decompose and turn into humus. The term "compost" is generally applied to the finished product, ready for use after decay of the organic matter, though it maintains the implication of being a mixture.

Much has been written about compost, and near-marvels are frequently attributed to its use. Nor is this a recent development; the very evolution of the word is proof of the ancientness of the practice. In Asia, compost has been employed for thousands of years, and that it is nothing new in the Western world either is attested, for instance, by the fact that over 100 years ago the "Gardener's Chronicle of England" published recipes for some 20 different types of compost, giving their uses.

Economic Importance of Compost

There is no denying the value of a properly prepared compost, especially for horticultural purposes, but, for an honest appraisal, this material must be considered soberly, without exaggeration, and most of all without clouding the issue with mysticism, as is so frequently attempted.

The appellation "artificial manure," which is frequently used for compost, offers a clue to its economic importance. As mentioned before, manure is becoming ever more scarce and is almost unobtainable in the immediate vicinity of large cities, where the intensive horticulture practiced by market gardeners creates the greatest demand for it. On the other hand, intensive cultivation can produce continuously high yields only when the required yet rapidly used-up humus is frequently replenished.

Losses and Expense in Production of Compost. It has long been observed that well-prepared compost is potentially richer in readily available plant nutrients, as well as better balanced in its composition, than the average farmyard manure, and this is borne out by chemical analysis. Gardeners generally prefer compost to farm manure, and even set manure up in piles to let it decompose for several months or even for a year or more before using it. What usually is not considered is that finished compost, at an average, represents no more than one quarter of the original bulk of the materials used. This is the reason—reduction in bulk—why the finished product is, pound for pound, richer even in nitrogen than were the basic materials, in spite of huge nitrogen losses during the decomposition processes. Therefore, it is unfair to compare the effect of compost with that of fresh manure, load for load. Actually, because of the losses especially of nitrogen, compost is a much more expensive material than farmyard manure, and the repeated handling which it requires, and which represents costly labor, renders it still more expensive. The commercial gardener may disregard this expense, because he raises high-value cash crops, and the use of plenty of compost permits continuous operation without rotation. The private gardener rightly prefers compost because of its safety and the simplicity of its use. Besides, he cannot obtain sufficient manure anyhow. The farmer, however, is in a different position.

Advantage of Summer Manure for Compost Production. To urge the farmer to compost all his manure before he applies it to the field is simply unrealistic, since this completely disregards the all-important economic factor. He must use the winter manure in the manner previously described, because he simply cannot afford the losses which would result from composting it. Summer manure, which cannot be stored profitably, is a different matter. A large part of the nitrogen contained in the summer manure is likely to be lost anyhow. Besides, it is mainly during summer, especially toward the end of summer, that all kinds of waste products, such as surplus straw, spoiled hay, vegetable residues, and remains of slaughtered animals are plentiful on a farm. These may be salvaged through composting. If these materials are set up properly together with some of the summer manure, a valuable compost will result which may be employed profitably during the following year.

Principles of Compost Production

How the various organic materials should be handled and treated in order to obtain a high-grade compost should hardly need further detailing if the preceding pages have been read with profit. The main principle involved is the reduction of highly complex organic compounds to much simpler and at least partly inorganic ones, which either are immediately available to growing plants or which readily become so when they enter the soil. The means by which this change is wrought are the life processes of microorganisms, bacteria, and fungi, which can do this work properly only under aerobic conditions (when oxygen is freely available). The most important compounds to be reduced are carbohydrates and proteins, and a mixture for producing the richest compost must contain proper proportions of both. This is the whole secret.

The manner in which carbohydrates and proteins decompose will not be repeated here. (See pages 55, 165, and 277.) Composting is merely the practical application of the principles previously described. The most important thing to remember is the desirability of accessory feeding of the microorganisms with inorganic fertilizers, in order to render their work more efficient; microorganisms are *not* injured by inorganic fertilizers, and the latter are readily used as food by the various bacteria and fungi concerned. For this reason, the fertilizers which have been added to the compost pile are not lost but largely appear again in the finished product, having been incorporated in the bodies of the microorganisms.

Layering of Materials. Most recipes for compost preparation recommend layering of the material in order to control as far as possible the proportion between carbohydrates and proteins, as follows: All plant remains, such as vegetable refuse, lawn clippings, weeds, leaves, straw, and spoiled hay, are largely carbohydrates and may be spread out in a 6-in.-thick layer. On top of this comes a 4- or 5-in. layer of manure. All manures, including the urine soaked up by the litter, are largely proteinic. So are all animal remains, including blood. (Kitchen garbage is likely to include both animal remains and vegetable refuse.) Over the manure should be spread a 1½- to 2-in. layer of the best topsoil available. This layering is repeated until a height of 5 or 6 ft is reached.

MODIFIED PROCEDURE. This procedure would produce an ideal compost pile, but usually manure is not available, and layering in this manner is possible only when all the materials required are at hand. This will rarely be the case and, in consequence, the above recipe is largely theoretical. It has been quoted here only to show ideal proportions. Under average conditions one will have to add to the pile whatever suitable refuse one has from time to time. The thickness of the layers can be disregarded, but, instead of simply dumping the various materials, such as lawn clippings or kitchen garbage, in one place, one should always scatter them over the whole pile. As far as possible, proteinic material should be alternated with carbohydrate material.

IMPORTANCE OF THE SOIL LAYER. More important than is generally realized is the addition of good topsoil which serves to inoculate the pile with the right type of microorganisms required for the decomposition processes. Even when manure is included, soil has to fulfill this function because, contrary to common claim, the bacteria contained in fresh manure cannot do the work of the soil microorganisms and die off rather quickly. The soil should be spread over the pile at least 1 to 2 in. thick, every time a layer of general refuse of 8 to 10 in. has accumulated.

ADDITION OF FERTILIZER. When no or only very little manure can be incorporated in the compost pile, fertilizer should be added to it. This has the purpose of stimulating rapid multiplication of the microorganisms and, therefore, will be most effective when scattered over each soil layer. Both manure and fertilizer should not be applied. Even in the manureless pile, fertilizer is needed only in the beginning. Once the microorganisms get going, they find all they need in the decomposing organic matter. In consequence, the required amounts are quite small. For a compost pile of mixed composition which is 6 ft wide and 15 ft long, it will be sufficient to add to each soil layer ½ to ¾ lb of a general fertilizer mixture consisting of 5 lb of ammonium sulfate, 1½ lb of superphosphate, 1 lb of muriate of potash, and 5½ lb of ground limestone. Proportionately smaller amounts should be applied to piles of lesser dimensions.

THE DOUBLE ROLE OF SUPERPHOSPHATE. Powdered limestone serves to compensate for the acidity of ammonium sulfate, and it may once more be pointed out that hydrated lime must under no circumstances be used to replace it, being unsuited for the purpose. (See page 203.) The superphosphate, besides supplying phosphorus for the use of the microorganisms, has the important additional function of tying up some of the free ammonia which develops, in the same manner as was described under manure. For this reason alone, it should never be omitted.

CHICKEN MANURE A VALUABLE INGREDIENT. One of the very best uses that can be made of chicken manure is to add it to the compost pile, because it is rather too concentrated to be applied directly to the soil. In the compost pile a 1-in. layer of chicken manure may replace 4 or 5 in. of cow or horse manure. There is, of course, no reason why chicken manure as well as farmyard manure could not be used together when both are available. No additional fertilizer is needed when chicken manure is incorporated in the pile.

MOISTURE AND AIR. Every layer of the compost pile must be well watered (not soaked but thoroughly moistened), because water is needed for the chemical process of hydrolysis. (See page 156.) Needed also is free access of air, since what is wanted are aerobic processes, not the anaerobic ones which would result in nitrogen losses. (See page 202.) This is in direct opposition to the procedure advocated for winter storage of manure, where decomposition of any type is suppressed as far as possible.

Assuring Entry of Air. The best procedure to assure the free entry of air is to set, at the very beginning, a row of thick stakes—about 3 ft apart—in the lengthwise axis of the pile, and to pull these stakes out when the pile is finished, leaving air holes in their stead. The top of the pile should slope to the center, so that rain water will not run off but will soak into it. In case the season should be dry, the compost pile must be watered from time to time.

Development of Heat in the Pile. The rapid oxidation which is thus induced will result in the development of heat. As long as sufficient moisture has been supplied, however, this heat will never become excessive. If no heat develops within about a week, the pile has been set up wrongly and must be restacked, since, otherwise, decomposition will be very slow and will not result in the best type of compost. This cannot happen if the procedure is carried out as described.

Turning the Compost Pile. Although this type of compost makes the best possible use of the various waste materials which accumulate on a farm, farmers frequently object that compost must be turned over in order to be any good (which is perfectly true) and that they can find no time for this work. The gardener turns his compost over at least twice at about four-week intervals, since this serves to speed up decomposition. On these occasions he always throws the outside of the pile into the center, so that composting will be more uniform. In this manner it is possible to obtain an excellent compost within 3 or 4 months.

A SIMPLIFIED PROCEDURE FOR THE FARMER. As was mentioned previously, the largest amounts of wastes accrue on a farm during late summer and fall. To set these up in orderly piles as they come to hand, throwing some manure in with them, is small additional labor, especially since there is no need at all to be pedantic about the thickness of the different layers. Some good soil must also be incorporated, and watering of the pile as it is being built must not be omitted. At the end of the season, when most of the farm labor is done, time can usually be found to turn the piles at least once. Thereafter, the compost piles can be forgotten until spring, and the rich compost, which by that time will have developed, will in value many times exceed the comparatively small amount of labor expended in producing it.

Fertilizer Value of Compost

As pointed out previously, organic materials, in decomposing, shrink to about one fourth of their original bulk. In consequence, the resulting compost is, pound for pound, richer in nutrient content than farmyard manure, regardless of the losses unavoidably incurred during decomposition. Naturally, the composition of the pile has a considerable influence on the quality of the resulting compost, and the greater the variety of organic materials which have been incorporated, the greater and better balanced is the nutrient value of the resulting compost. In general, one may say that 6 tons/acre of good compost are the approximate equal of 10 to 12 tons of farmyard manure.

Amounts of Compost Required to Supply All Needs

It has been claimed that 5 tons/acre/year of a first-class compost are sufficient to supply all fertilizer needs of crops. This is rather over-optimistic, though it depends, of course, upon the original condition of the soil. Amounts to 10 tons/acre/year are more likely to produce significant results, and it may well take 15 or even 20 tons/acre/year to supply enough nutrients to a crop for a reasonably high yield. The vast variety of different soils, each with its own individual needs, will never permit the establishment of an absolute norm. It is certain, however, that to supply all nutrient needs of all the farms of a country, for instance the United States, with compost alone would require such fantastic amounts of organic materials that they could never be made available. A 100-acre farm, for instance, would require 1,000 tons of compost/year. To produce this amount, at least 4,000 tons of organic matter would have to be composted. Where is this to come from year after year? Besides, to compost so much would require a great deal of labor, which not only cannot be made available but also would raise costs to an entirely uneconomical level.

The Economic Factor in an All Compost Culture

As far as farming is concerned, compost can never be expected to be more than an aid; it must not be neglected, but it will serve mainly to assist in maintaining a satisfactory humus level. The situation is different when only a few acres are kept under intense cultivation, as in truck gardening. Under such conditions it is possible to get along with nothing but compost. Whether in the long run, however, it will not be much more economical, even in truck gardening, to use less compost and to supplement it with applications of inorganic fertilizers is another question. All sober calculations point to the fact that this will be the case.

Artificial Manures

It still remains to discuss the composting of certain specific materials, such as straw, leaves, wood chips, sawdust, ground corncobs, spent hops, cotton husks, and peanut shells, which, in themselves, contain very little of plant nutrient substances. As was explained before (page 198), when such materials are added directly to the soil, they decompose very slowly, producing a temporary soil deficiency, especially of nitrogen but also of other plant nutrients.

When properly set up for composting, mixed with appropriate amounts of inorganic fertilizers to supply the microorganisms, any or all of the above-mentioned materials will produce an excellent compost which, in nutrient value, may be fully equal to farmyard manure.

Principles of Composting Materials with Low Nutrient Content. The procedure consists in reducing the cellulose and lignin of these materials to humus, which then becomes loaded up with the nutrients originally contained in the inorganic fertilizers. The latter by then have been largely converted into organic compounds, since they were incorporated in the bodies of the microorganisms. The finished compost is quite similar in its action to farmyard manure, and it is for this reason that such composts, in particular, are frequently termed *artificial manures*. The principles involved are very much the same as with the production of other compost, except that in this case all the required nutrients are supplied artificially. For this reason it is important that, from the very beginning, the fertilizers are thoroughly mixed with the materials which are to be composted. In addition, it is advisable to sprinkle some good topsoil over the material as it is being piled, though there is no need to attempt layering. Thorough watering and aeration are as important as with other compost. Aeration is a critical factor, in particular with such materials as sawdust or spent hops, which are inclined to pack down tightly, and for this reason these are best mixed with other loose materials such as straw.

Amount of Inorganic Fertilizer Required. The amounts and ratio of fertilizers to be added for the production of this type of artificial manures are best computed by assuming that neither nitrogen nor phosphate is present at all—the actually present amounts are really quite negligible

—and by taking into account that the potassium (K_2O), which is present in fair amounts, becomes available only very slowly. On this basis one arrives at the following average figures per ton of dry material:

100	lb of ammonium sulfate (20 per cent)
20	lb of superphosphate (20 per cent)
8	lb of muriate of potash (55 per cent)
110	lb of powdered limestone[4]

These figures are rather at variance with the amounts generally recommended in published recipes, but, in practical application, they will be found to be much more in accord with actual requirements.

DIRECTIONS FOR THE PRIVATE GARDENER. The private gardener who handles smaller amounts may simply divide the above figures by 10, which would give him: 10 lb of ammonium sulfate, 2 lb of superphosphate, ¾ lb of muriate of potash, and 11 lb of powdered limestone. These four ingredients must be thoroughly mixed and may be applied to approximately 200 lb of leaves or whatever other similar material is to be composted. If much of the material used by the home gardener consists of kitchen garbage, the amount of the ammonium sulfate and powdered limestone may be reduced by half. If chicken manure or other manure is added also, it is best to follow the first-outlined procedure, and very little fertilizer will then be required.[5]

URBAN WASTE MATERIALS AS SOURCE OF ORGANIC MATTER

The waste materials—rubbish, garbage, and sewage—which accumulate wherever people live together in larger towns and cities represent one

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[4] An amount of 100 lb of ammonium sulfate/ton of dry straw or similar material represents 1.0 per cent of nitrogen which, in general, is amply sufficient for satisfactory decomposition. [According to F. C. Gerretsen, *Plant and Soil* (1949), 0.7 per cent nitrogen is sufficient.] At the ratio 5–1–2 (see page 381) the proportionate amount of phosphate is represented by 20 lb of superphosphate (20 per cent)/ton. The corresponding amount of potassium (K_2O) would be represented by 16 lb of potassium sulfate/ton, but, since a certain amount of potassium is present and additional supplies are needed mainly in the beginning, this amount may be reduced to half, viz., 8 lb/ton. When urea (46 per cent nitrogen) is used as nitrogen source, only 50 lb/ton need be applied, whereas the amount of ground limestone, required to compensate residual acidity, will be reduced to 38 lb/ton. Of ammonium nitrate (33 per cent nitrogen), 60 lb plus 36 lb of compensating ground limestone/ton would be required.

[5] A mixture of 1 part chicken manure, 2 parts sawdust, and 1 part straw or freshly cut plants (silage), with some soil sprinkled over it and kept well watered, decays sufficiently in 12 months.

of the greatest problems of civilization. They have to be collected regularly and disposed of in sanitary fashion, since to allow them to accumulate would create a menace to the health of the inhabitants. Those who are awake to the necessity of providing sufficient organic matter for humus-starved cultivated soils have, for a long time, had their eyes on the large amounts of organic substances contained in these urban waste materials, with the view of salvaging them in one way or another for agricultural purposes. So far, unfortunately, none of the methods which have been proposed or are employed has salvaged more than a fraction of the original amounts of these organic wastes. The difficulty, though, lies not with the processing, which can be handled easily, efficiently, and economically, but with the collecting, specifically with the separation of the usable from the nonusable materials after they have been collected. Since frequent reference is made in the literature to these urban waste materials, coupled with urgent appeals to salvage them for fertilizer purposes, a short discussion of the problems involved and the progress made to date may be of interest.

Sewage

Human Excrement in City Sewage. The most important component of sewage is represented by the human excrements which, as need not be emphasized, are of considerable fertilizer value. The so-called "night soil" of the Chinese is nothing but fresh human excrement. Though this has been the great fertilizer stand-by of the Asiatic peoples for thousands of years, the manner in which it is gathered every morning and immediately carried to the fields is highly offensive as well as unbelievably insanitary. Still, the fact that this material has been used for so long and so effectively in Asia makes one ponder how much of intrinsic value is actually wasted with modern sewer systems. It has been estimated, for instance, that a large city, such as greater New York with a population of approximately 10 million people, wastes with its sewage annually the equivalent of 85 million lb of nitrogen, 26 million lb of phosphorus (as P_2O_5), and 21 million lb of potassium (as K_2O).[6] These figures are computed solely

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[6] One person produces, per year, an average of 1,000 lb of excrements, 90 per cent of which is urine. Analysis of mixed excrements has given the following values in percentage:

Water	93.70
Organic matter	4.90
Nitrogen (N)	0.85
Phosphorus (as P_2O_5)	0.26
Potassium (as K_2O)	0.21
Calcium (as CaO)	0.08

from the human excrements contained in this sewage and do not include the additional large amounts of organic matter discharged into the sewer with the waste waters from restaurant kitchens, abattoirs, canneries, starch factories, breweries, etc.

These amounts are impressively high, in spite of the fact that they represent only the wastes from one very large city. There is no doubt that, if it were possible to salvage these valuable fertilizer materials not only from New York but also from all other large cities, it would make a very big difference indeed for agriculture in general. Unfortunately, the chances are extremely slim that anything even approaching such a happy state can ever be achieved.

Necessity of Separating Usable from Nonusable Sewage. The main difficulty obstructing complete success is found in the fact that, in many cities, waste waters from hospitals, chemical factories, and other industries which employ large amounts of various chemical substances are included in the general sewage. Some of these frequently poisonous substances are impossible, or at least very costly, to remove afterward.

One solution to the problem would be to require by law that all industries and other establishments likely to discharge poisonous substances into the sewer must install their own filtering and clearing tanks. This is ever more frequently done, especially in the interest of preventing river pollution. All such regulations, however, are very difficult to enforce, are easily violated, or are carried out inefficiently. Except where a factory has its own sewer outlet directly into the river, full control is next to impossible.

Much more effective is segregation, either of the industrial establishments in one section of the city where they can have their own sewer, or of the sewer systems of the different sections of a city. In the latter case the sewage from those sections which do not contain any objectionable industries can readily be separated from that of the others. Either one or the other of these systems is in operation in many European cities.

One other difficulty in the way of sewage salvage—the high dilution of the sewage caused by the large amounts of water which it contains—is much easier to overcome. In fact, most sewage processing plants are based on existing installations whose primary purpose was to remove most of the putrescent substances from the sewage water so that the latter could be discharged into a river in a more sanitary manner and without offensive odors.

The various methods which may be employed either to clear sewage water or to recover sewage wastes cannot be discussed here in detail; a general summary giving merely the most pertinent facts must suffice.

CLEARING SEWAGE WATER AND RECOVERING WASTES

Mechanical Processes

Under this heading fall those procedures which have for their main purpose a preliminary cleansing of the sewage water so that it may be discharged into a river without causing offense. Such an installation consists of a series of sedimentation tanks, of varying construction, through which the sewage is conducted. The solid substances, including the various colloids, fats, and silty mud, are thus caused to settle to the bottom, and approximately 65 to 70 per cent of the undissolved substances may, in this manner, be separated from the rest of the sewage. This results in the loss of all dissolved substances. In addition, the resulting mud or sludge, as it is usually called, is rather difficult to dry economically so that it can be handled, and its usability for fertilizer purposes depends on the exclusion of industrial wastes from the original sewage. The fertilizer value of such sewage sludge, even when it is completely free of any poisonous substances, is rather low and has the added disadvantage that it decomposes very slowly in the soil, owing to the above-mentioned loss of all readily soluble compounds. Recent attempts to "vitalize" this type of sludge through steam treatment have been quite successful, but they cannot make up for the huge losses which unavoidably result from purely mechanical methods of sewage clearing.

Chemical Processes

Rapid clarification of sewage water by means of chemical treatment is readily possible and has been carried out repeatedly. The principles on which such procedures are based are identical with those which are employed in the purification of more or less turbid lake water for use in a city water-supply system. In the main, the method consists in adding carefully calculated amounts of aluminum sulfate or ferrous sulfate (copperas) and in adjusting the pH of the water through the addition of appropriate amounts of hydrated lime [$Ca(OH)_2$].

The chemical reactions which are thus initiated—in particular hydrolysis and hydration (see page 156)—result in the production of hydroxides. These latter, being insoluble, precipitate, and in settling take a large part of the other floating impurities with them, resulting in rapid clearing. The tanks employed for the purpose are very similar in construction to the sedimentation tanks mentioned above. The water insolubility of the hydroxides of aluminum and iron renders them inert, so that they do not impair the value of the sludge, and the sulfuric acid which evolves is neutralized by the lime. Actually, this procedure of separating the sewage from the water is the most efficient of all and may, under careful supervision, result in the production of a rather high-value sludge. The main disadvantage is that the chemicals required are not cheap enough to make large-scale applications economically feasible. Besides, there is constant danger that surplus amounts of the chemicals used may be discharged into a river where, for considerable distances, they have the effect of diminishing or even preventing the biological self-purification of the river water. For certain industrial wastes, chemical treatment will often be the only satisfactory method.

Biological Processes

As the name implies, these procedures depend upon bacteria to process the sewage. There is no doubt that they are effective in practice as well as economically feasible. Poisonous industrial wastes must be excluded from the sewage in these procedures as well as in all others.

The Sewage Farm. The most obvious and most natural way of using sewage for agricultural purposes is merely an extension of the Chinese application of night soil; the method employs special sewage farms which are irrigated with city sewage. This has been practiced in Europe on a fairly large scale, and rather successfully at Paris and Berlin. The main requirement for success is a readily draining, very light sandy soil. Even the almost sterile sand of seacoast dunes has been rendered fertile through sewage irrigation—for instance at Danzig on the Baltic Sea. Heavy clayey soils or peaty soils are unsuitable for this purpose.

The main disadvantage of sewage farming is that highly offensive odors are unavoidable, which makes it necessary to find a location sufficiently far away from habitations as well as from public roads. On the other hand, the sewage farm must not be too far outside the city, since the expense of pumping the sewage increases, of course, with distance.

Farming with Complete Sewage. A rather large area is required for this procedure, since it consists in first flooding a piece of land with sewage and allowing the latter to drain away completely. This may be repeated a number of times, but after a while a state of saturation is reached which makes a rest for several years necessary. During this rest period the land is cultivated and planted with various crops. That successful sewage farming requires considerable experience, especially as far as drainage, liming, and the selection of suitable crops are concerned, will need no emphasis. In general, it can be said that this procedure holds real promise only for medium-large cities with large tracts of worthless sandy land in their immediate vicinity.

It has been computed that, depending on soil conditions, farming with complete sewage requires 2½ acres to take care of the sewage produced by 200 to 400 people.

Irrigation with Sewage Water. It is possible also merely to irrigate a farm with the liquid sewage after most of the solids have been removed through sedimentation. This is a very promising procedure, since it permits making the best possible use of all the valuable dissolved sewage substances which generally are lost altogether. With this method, 2½ acres of land are sufficient to take care of the sewage water produced by as many as 1,200 people. The sludge obtained from the sedimentation tanks can be used separately.

Fishponds for Clearing Sewage Water. An additional interesting possibility is the use of specially constructed fishponds for the clearing of sewage water. One experimental installation of such fishponds near Strassbourg, covering approximately 5 acres, proved sufficient to take care of the sewage water (not the complete sewage!) produced by 4,000 people. The fish (carp, tench, and rainbow trout) which weighed an average of 1 lb each when liberated in the ponds in spring, weighed from 4 to 6 lb each by fall. Their flavor was excellent, and the overflow water from the ponds was perfectly clear. Numerous similar installations—one near Munich covering over 500 acres—have since proved the complete practical as well as economical feasibility of this procedure which deserves thoughtful attention.

Artificial Biological Processes. Particularly promising are the so-called artificial biological methods which, because of their high efficiency and ease of operation, are ever more frequently employed. In this procedure the undissolved sewage materials are usually separated from the liquid through one of several sedimentation processes, and the two are then treated separately. The liquid is conducted slowly and in fine dispersion through specially prepared filters of gravel, coke, crushed brick, etc., and is cleared by the bacteria inhabiting the filter material through oxidation, in very much the same manner in which a river purifies itself. The sedimentary mud (sludge) is conducted into digester or decomposition chambers of varying construction, where it likewise is subjected to bacterial activity.

THE IMHOFF TANK. These chambers usually are closed, such as the Imhoff tank, which produces entirely anaerobic decomposition. This process, which is completely free of offensive odors, results in the development of considerable amounts of gases, especially methane gas

(CH_4), which may be employed as fuel for power engines or may be used as an admixture to illuminating gas produced in city gasworks. Approximately 1 cu ft of gas with 65 to 80 per cent methane content may be obtained from 100 cu ft of sewage. This procedure, therefore, appears to be economically rather advantageous, especially since the operation is almost automatic and requires a minimum of attention. The surplus moisture is removed from the sludge by means of specially constructed centrifuges.

AEROBIC PROCESSING OF SEWAGE FOR FERTILIZER. To produce so-called "activated sludge," the sewage is passed through open tanks which are kept thoroughly aerated either through continual stirring or by injecting air at the bottom of the tank. The oxidizing bacteria, instead of clinging to the filter material as described above, are free floating in the liquid. The resulting sludge consists of flocculent aggregates which, after being separated from the liquid in special sedimentation tanks, are passed through digestion chambers similar to the Imhoff tank.

Activated sludge produced in this manner, or through one of several methods combining open-tank with filter treatment, is generally superior for fertilizer purposes. Enrichment in vitamin B_{12}, resulting from the activities of certain microorganisms which thrive under these particular conditions, has been proved beyond doubt. Several products of this type are sold commercially such, for instance, as "milorganite" which is produced in large quantities in the city of Milwaukee. This contains approximately 6 per cent nitrogen and 2.5 per cent phosphorus pentoxide. A similar product is "nitroganic" which is manufactured in Pasadena, California. Various other American cities, such as Chicago, either have or are developing plants for the production of fertilizer from sewage. All types of sewage sludge contain trace elements which add to their value. Their potassium oxide content is always low and must be adjusted through the simultaneous application of potassium fertilizer. The "Fraser compost," which lately has come into prominence, may also be mentioned in this connection. Though it uses, besides sewage sludge, various other waste organic materials, it employs digester or decomposition chambers very similar to those described above for sewage processing. The resulting organic fertilizer is somewhat richer than milorganite and compares favorably with the best type of compost.

DESIRABILITY OF PROPER SEWAGE PROCESSING. No doubt remains that proper disposal of sewage will become an ever more pressing necessity as more people tend to congregate in large cities. Certainly it is high time that the appalling pollution of rivers be stopped. The expense involved in sewage disposal will always be amply balanced by gains in sanitation alone. In addition, the application of some of the procedures mentioned above may result in considerable savings from salable byproducts. Approximately one quarter of the total cost of sewage disposal may well be recovered in this manner. The choice of procedure or combination of procedures will have to be decided for each case, since this must be governed by circumstances.

Garbage

The garbage accumulating daily in every household likewise presents a considerable and expensive problem in every city, since it has to be collected and disposed of. Yet, as much as 50 per cent of the average garbage usually consists of organic matter, which is potential humus, and which would be of value for agricultural purposes if it could be salvaged. Many attempts have been made to do this, but no entirely satisfactory method has so far been found.

The main difficulty lies in the all inclusiveness of the mixture which the average garbage can contains, and which may include, besides the above-mentioned organic matter, ashes, clinkers, paper, tin cans, broken glass, earthenware, and anything else which a human being uses in his home.

Separating Garbage at the Source. The most satisfactory solution would undoubtedly be to separate this material at the source by educating citizens to use two garbage cans, one for the decomposable and another for the nondecomposable material. Simple as this appears to be, all attempts to put such a system into practice have failed, even when each householder was supplied free of charge with two clearly marked garbage cans of different shape (one round and one square). For some reason it seemed impossible for the average housewife to remember what to put where, and in most instances both cans contained an equally hopeless mixture of everything. This is a great pity, since there is no other equally simple way of separation, and the organic matter, if it were possible to gather it separately, could readily be processed in decomposition chambers and could be turned into highly useful as well as readily salable fertilizer material.

Sorting Garbage After Collection. Many attempts have been made and are still being made to sort the garbage after collecting. Installations which serve this purpose remove metals by means of magnets and pass the garbage through or over different-sized screens to remove other matters. A certain amount of hand sorting, however, is unavoidable. The compost which is finally obtained in this manner is rather low in content of plant nutrients, and most European garbage-sorting plants operating according to the above principles have been discontinued as uneconomical.

Sanitary Garbage Disposal. It is for this reason that many large cities now incinerate all garbage, using the ashes to fill abandoned quarries, etc. This is a sanitarily satisfactory solution, though otherwise it is as wasteful as it is expensive. Still, this procedure is preferable to piling the garbage in open dumps where it serves as a breeding place for rats and flies. To dump garbage into the ocean, as is sometimes done, is not much better, since, even when it is dumped far out, some of it is bound to be washed ashore sooner or later. So-called "sanitary fill"—the burying of mixed garbage in parallel trenches in low-lying areas which thus are raised and become usable for park or playground development—is probably the best means of useful disposal. The problem of processing garbage for humus recovery in an economical and perhaps at least partly profitable manner still awaits a perfect solution.

Slaughterhouse Wastes

Tankage. The refuse from slaughterhouses also falls under the heading of urban waste materials, since most slaughterhouses are maintained in connection with large cities. The material itself, however, is quite different from sewage or garbage in so far as it is rather uniform and, therefore, lends itself exceptionally well to processing for salvage. Tankage is composed of meat scraps, intestines, bones, and carcasses of dead or condemned animals. These materials are cooked under steam pressure, grease and tallow are removed, and the solids, separated from the tank water, are dried and ground to meal. Such tankage, sometimes termed "blood and bones," makes an excellent fertilizer for nitrogen and phosphate (its potassium oxide content is very low). It decomposes in the soil somewhat more slowly than dried blood.

Dried and ground tankage is a brownish powdery material with a content of 7 to 10 per cent nitrogen and 10 to 15 per cent phosphorus (as P_2O_5).

Dried Blood. The blood of slaughtered animals is usually processed separately. It is pumped into coagulating tanks where it is cooked until it coagulates. After standing a few hours, water settles out at the bottom and is drawn off. Cooking then is continued until all water is removed, and the remainder is ground into a dark-colored meal. Such dried blood has a total nitrogen content of 10 to 17 per cent. Naturally, it contains also all the other mineral components of blood, such as calcium, magnesium, iron, sodium, potassium, phosphorus, chloride, and sulfate, though the amounts of any of these are rather small. Phosphorus content, for instance, varies from 0.3 to 1.5 per cent (as P_2O_5) and potassium from 0.5 to 1 per cent (as K_2O). The fertilizer value of dried blood, therefore, rests mainly on its content of nitrogen which becomes very readily and rather quickly available to plants when this material is added to the soil. In this important respect dried blood is superior to all other organic fertilizer materials, and its content of certain minor elements may well be worthy of consideration also. Occasionally, dried blood is fortified through the addition of potassium salts and phosphate to compensate for its low content of these elements, and in this manner a very excellent fertilizer may be provided. Unfortunately, its cost is rather too high for general use, and the amounts available are limited. All better grades of dried blood are in great demand for stock-feeding purposes.

Bones. BONE MEAL. The fertilizer value of bones has been recognized for a long time, though when buried whole they decompose very slowly. Even when added to the compost pile, bones should at least be smashed with a hammer. For fertilizer purposes, bones must be ground as fine as possible. Meal made of raw bones is no longer available because the fat they contain (approximately 10 per cent) is too valuable to be lost. Actually, this removal of the fat—by means of a solvent such as benzene or naphtha—is an advantage as far as fertilizer value is concerned, since the water-repellent fat retards the decomposition of the phosphates in the soil.

Meal made of bones, after the fat has been removed, contains from 3.5 to 4.5 per cent nitrogen and from 20 to 25 per cent phosphorus (as P_2O_5).

STEAMED BONE MEAL. Bones usually are steamed after fat removal in order to remove the organic substances which are used for the production of glue and gelatin. The meal made from steamed bones, usually termed "steamed bone meal," is the type which is most commonly available commercially, and contains from 0.5 to 1 per cent nitrogen and from 28 to 32 per cent phosphorus pentoxide. As can be seen, its content of phosphate is higher than that of unsteamed bone meal. This results from the loss in bulk through the removal of the organic matter. Actually, this is not the advantage it seems to be, since the phosphate of steamed bone meal is much less readily available to plants, and the loss in nitrogen is a further disadvantage. Since glue and gelatin are valuable by-products, meal made of unsteamed bones is quite as rarely available as raw bone meal.

Since the advent of the much more economical and much cheaper superphosphate, bone meal in any form has pretty well lost its importance. It is still used mainly by conservative gardeners who prefer its slow action because of its safety, and who do not realize that especially in a neutral or alkaline soil very little of the phosphate contained in bone meal will ever become available. That steamed bone meal is one of the least economical ways in which phosphate can be supplied under any circumstances should be considered also.

BONE SUPERPHOSPHATE. Acidulated bone meal, or bone superphosphate, is now only of historical interest, since it is no longer manufactured. It was produced by treating bones with sulfuric acid, which resulted in converting part of the tricalcium phosphate into monophosphate, therewith increasing availability. This is the same procedure employed in producing superphosphate from phosphate rock, and the main difference between the two products is that bone superphosphate is much more expensive.

BONE ASHES. In the same category of merely historical interest belong the bone ashes which formerly were exported from South America. They resulted as a by-product from the manufacture of meat extract, where bones were used as fuel. Bone ashes contain as much as 85 per cent tricalcium phosphate and, therefore, have considerable value as phosphate fertilizer. They are no longer available.

BONE CHARCOAL OR BONE BLACK. Sugar refineries employ bone charcoal —produced by heating granulated bones to incandescence under exclusion of oxygen—to decolorize the sugar extract before dehydrating it. When no longer usable, this bone charcoal is discarded and may then serve as a rather effective, though slow-acting, fertilizer. It contains approximately 10 per cent carbon, 1 to 2 per cent nitrogen, and 30 to 35 per cent phosphorus pentoxide. This material is available only in the immediate neighborhood of sugar factories.

Hoof and Horn Meal. The albuminous substance keratin, which is the main component of horns, hoofs, claws, and hairs, decomposes very slowly in the soil, even when such materials are ground to a fine powder. Meal made of hoofs and horns—sometimes the two are sold separately, hoof meal being preferred—contains from 12 to 16 per cent nitrogen as well as 3 to 5 per cent sulfur. Approximately 50 per cent of it is carbon, the rest being mainly hydrogen and oxygen. The analysis suggests that this is essentially a very slow-acting nitrogen fertilizer as which, in fact, it commonly is advertised. The value of this material as a nitrogen fertilizer, however, can be no more than negligible, and its price is always comparatively high. Its persistent popularity in Europe, recently on the increase in America also, cannot rest on this premise, but a curious use made of hoof and horn meal by greenhouse gardeners presents a valuable clue to the growing demand. This consists in sprinkling the meal on the benches holding potted plants or even on the greenhouse floor, which has a seemingly miraculous, stimulating effect on the growth of hothouse plants. Actually, this procedure results in the slow but steady release of carbon dioxide which, in a warm greenhouse free of drafts, cannot fail to exert a beneficial influence. When hoof and horn meal is incorporated in the soil of potted plants the same reaction takes place, and the developing carbon dioxide and carbonic acid, probably together with small amounts of sulfuric acid, will then assist in making other nutrient substances—possibly even certain minor elements present in this material—more freely available.

MANUFACTURED OR BY-PRODUCT ORGANIC FERTILIZERS

Many organic fertilizers result from various industrial wastes which frequently are merely dried and ground into meal. All those mentioned in the subsequent paragraphs have in common that they add only negligible amounts of humus to the soil. Many of them also are very low in nutrient content, and some are mentioned merely for completeness' sake, so that those who are contemplating their use may form an opinion of the effect they are likely to produce.

One important attribute of some of them, especially of the various types of guano as well as the oil cakes and seed meals, which should not be overlooked is that they contain various trace elements. Especially under conditions of intensive cultivation, this fact may sometimes make their use well worth while.

Guano

The fertilizer material sold under the name "Peruvian guano" or simply "guano" falls under the heading of manufactured fertilizer only because it is sifted, dried, and ground before it is marketed. It is a natural product, consisting of the excrements of sea birds which accumulated over many centuries, in particular on certain arid tropical islands of the Pacific Ocean. At the Chincha Islands on the coast of Peru, the guano layer was 60 to 100 ft thick.

Large quantities of guano were first exported from these islands during the middle of the last century, though the native Peruvians knew the value of this material as fertilizer and used it centuries ago. A. von Humboldt, the famous traveler, took a sample of it to Europe in 1804. By now, the Peruvian deposits are quite exhausted and, though further deposits have been located on islands along the coasts of Mexico, Chile, and Patagonia, the world's demand for guano has diminished even more than its supply. The great irregularity in the composition of such guano and the increasing utilization of more readily available local materials in the various countries are responsible for the lessening demand.

As must be expected, guano is not unlike chicken manure, though it is even more concentrated. Its content in nitrogen and phosphate (potassium content is always rather low) varies with the age of the deposits as well as with the climatic conditions of the locality from which it comes. High-grade Peruvian guano or guano from Southwest Africa may contain as much as 11 to 18 per cent nitrogen, 8 to 15 per cent phosphorus (P_2O_5), and 2 to 3 per cent potassium (K_2O).

Guano from Indian Ocean islands, for instance from the Seychelles, where rainfall is higher, may contain no more than 1 to 2 per cent nitrogen, and its phosphorus (P_2O_5) content may be as high as 25 per cent or even higher.

Commercially sold guano sometimes is adulterated with gypsum, sawdust, etc., which greatly lowers its fertilizer value. Therefore, one should never buy guano which is not accompanied by a statement of its analysis. So-called "fortified guano" contains additions of artificial fertilizer salts, but its price is rather high.

Bat and Seal Guano. Occasionally, bat guano is available locally where deposits have been found in large caves (for instance in Missouri, Indiana, and New Zealand). This material contains approximately 8.5 per cent nitrogen, 5 per cent phosphorus (as P_2O_5), and 1.5 per cent potassium (as K_2O).

Seal guano, formerly obtained from islands where these animals congregate to bear and rear their young, is at present without importance, though it can, of course, be used where available.

In general, except where it is produced locally, for instance in Peru and Chile or South Africa, guano has lost most of its former importance as a fertilizer. It has no residual effects, lasting only for one season and therefore, at least as far as its nitrogen-phosphorus-potassium content is concerned, it is readily replaceable by various much cheaper artificial fertilizers.

Fish Meal

Fish meal (or fish guano), is a true industrial waste product, since it is usually made from offal as well as from undersize or otherwise unusable fishes which accumulate in seaboard fish markets or in some of the canneries. As much as 3 tons a day of such fish offal becomes available in some of the larger fishing harbors. This material is first steamed, mainly in order to sterilize it and to remove as much as possible of its highly offensive odor. Thereafter, it is dehydrated in continuously operating vacuum driers and finally is ground to meal.

The nitrogen and phosphate content of such fish meal varies widely, depending upon the percentage of fishbones contained in the original offal. It may contain from 5 to 10 per cent nitrogen and from 5 to 15 per cent phosphorus (P_2O_5). When added to soil, fish meal decomposes very rapidly, and its unpleasant odor, which is often objectionable, disappears equally quickly. Its fertilizer effect is pretty much the same as that of equivalent amounts of artificial fertilizers, and its action—like that of true guano—is limited to one season, without residual effects.

Since fish meal is in great demand as an admixture to poultry feed, the amounts available for fertilizer purposes are very limited.

Fish emulsion, an almost odorless liquid, is an excellent and complete though mild fertilizer used in special cultures, such as orchid growing.

Leather Meal

Leather wastes of factories making boots, gloves, etc., were formerly steamed and then ground to meal which was sold as a nitrogen fertilizer. Such meal contains approximately 6 to 10 per cent nitrogen as well as small amounts—0.5 to 1 per cent—phosphorus (as P_2O_5). The fertilizer value of this material is very low, and it is now of little more than historical interest, most of it being employed for other purposes.

Tobacco Dust

The dust-fine residue accumulating in tobacco-processing factories is an interesting material. Its fertilizer value is rather low, though it is comparatively rich in potash (6 per cent potassium oxide) and contains a fair amount of nitrogen (2 per cent). What makes it valuable for specific purposes, particularly in pot-plant culture, is the fact that it is alkaline in reaction yet is an organic matter which turns into humus. Its nicotine content is of interest also. Potted cacti, for instance, which are very subject to attacks by root lice, are often benefited by the addition of small amounts of tobacco dust to the soil. The mild fertilizer effect plus humus in an inoffensive form—most cacti prefer an alkaline soil—adds to its usefulness. In general, this material is of no more than limited importance. Other tobacco wastes, such as stems and spoiled leaves left over after harvesting, may be plowed under as is any other green manure for the purpose of adding humus to the soil, or may be composted.

Wool Wastes (Shoddy)

Most of the usable wastes resulting from the combing, washing, weaving, and spinning of wool, carpet cutting, etc., are now reclaimed, but, in the vicinity of mills or factories engaged in such work, a certain amount of wool wastes is frequently available and may be employed locally for fertilizer purposes. Depending upon its composition, wool shoddy contains from 3 to 15 or even 17 per cent nitrogen which, in the soil, becomes available gradually over a period of 3 to 4 years (approximately half of it in the first year).

Cottonseed Meal and Oil Cakes

The residue remaining after the oil has been pressed out of cotton seeds is sold as cottonseed meal and is used either for cattle feed or as a mild, rather slow-acting fertilizer. It contains from 5 to 7 per cent nitrogen, 2 to 3 per cent phosphorus (as P_2O_5), and 1 to 2 per cent potassium (as K_2O). When this material is added to soil, most of its plant nutrient content becomes available during the first year, and there is usually only a minor residual effect during the second or third year. Cottonseed meal is employed mainly where it is produced—viz., in cotton-growing regions—because transportation would raise its price beyond its value.

Other types of oil cake, such as linseed cake, rape cake, castor-bean cake (castor pomace), soybean cake (in China), etc., may likewise be used for fertilizer purposes, though these materials are in rather high demand for cattle feed. The nitrogen-phosphorus-potassium content of such oil cake is very similar to that of cottonseed meal.

Scotch Soot

Until a few years ago considerable amounts of soot were exported from Scotland, and this soot was used widely for fertilizer purposes on the European continent as well as in North America. Commercial or private growers of potted plants thought very highly of Scotch soot. Lately, this material has completely disappeared from the market, and even English seedsmen do not carry it in stock anymore. The reason appears to be that nitrogen, which ranges from 3 to 11 per cent (as ammonium sulfate), has come to be considered as the only effective ingredient of soot, and ammonium sulfate may, of course, be applied more economically in the form of the pure salt. This conception, however, may be erroneous, because spectrographic analysis reveals that Scotch soot contains the following minor elements:[7] 0.1 to 1 per cent aluminum, barium, boron, calcium, iron, magnesium, sodium, silicon, titanium, and zinc; 0.01 to 0.1 per cent chromium, copper, manganese,

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[7] This analysis was kindly supplied by the Laboratories of the Department of Mines, Quebec, P.Q., Canada.

nickel, lead, strontium, and zirconium; and 0.001 to 0.01 per cent tin and vanadium.

It is entirely possible that, in the forced feeding of potted greenhouse plants, some of these minor elements become critical, and that then the small amounts applied with the soot make an important difference. The facts are that top-dressing with soot produces, within a few days, unmistakably beneficial effects in the greater vigor and health of the plants, and the roots actually show a tendency to come to the surface for closer contact with the soot. An application of ammonium sulfate produces no comparable effects. Which of the above-listed minor elements may be the crucial ones still remains a moot question deserving of further investigation.

The only soot of real interest is that which results when soft coal is burned in open grates. This is the reason why Scotch soot is a superior type. Flue dust or soot from hard-coal-burning furnaces is not only valueless but may even contain harmful substances. Soot from wood-burning fireplaces is quite worthless.

Fertilized Peat

By itself, peat is not a fertilizer, since it contains only minute amounts of substances which, after decomposition, may serve as plant nutrients. The addition of peat, which may consist of about 90 per cent or even more of organic matter, is likely to be highly beneficial to a soil poor in humus content, but, as explained elsewhere, this effect is indirect and has nothing to do with the nutrient contents of the peat.

Peat readily adsorbs considerable amounts of various cations, however, such as the NH_4^+ (ammonia) ion or the phosphate (P_2O_5) ion, which in the soil become gradually available.

Procedures to prepare such fertilized peat are still largely in the experimental stage, though such products as "ammoniated peat," "Humo Ammophos," and "Stimulax peat," which now are occasionally offered, show the trend of possible future development.

27. INORGANIC OR MINERAL FERTILIZER MATERIALS

MAIN DIFFERENCES BETWEEN ORGANIC AND INORGANIC FERTILIZERS

Most of the inorganic fertilizer materials contain the various nutrient elements in readily available form, a fact which must be considered in evaluating them. As plant nutrients, they supply exactly the same ions which plants obtain from organic fertilizer materials after the latter have been decomposed.

The main difference between organic and inorganic fertilizers is that the former become available gradually (sometimes over several years), whereas the latter, in most instances, are available immediately. Both have advantages as well as disadvantages. Organic fertilizers are milder in their action and, therefore, safer for the unskilled user. On the other hand, as was shown in the preceding discussion of manure, compost, etc., they are quite low in their content of the three most important nutrient elements, viz., nitrogen, phosphorus, and potassium. Since the very large amounts of organic fertilizers which would be required to provide optimum conditions are rarely obtainable, supplemental applications of nitrogen, phosphorus, and potassium in mineral form are, in most instances, quite unavoidable if best results are to be achieved. Besides, the maximum requirement of plants for any one of these three elements varies with the season as well as with the type of plant, and to make sure, under different circumstances, that each element is available in optimum quantity when it is most wanted is much easier to achieve with mineral fertilizers than with organic ones.

The economic factor which, especially where large areas are concerned, definitely favors mineral fertilizers must be considered also. This economy derives primarily from the fact that single inorganic fertilizers permit to add to this soil only what actually is lacking, as established by means of soil analysis. The humus supplied by many organic fertilizers must be considered by itself, quite separately from the mere supply of required nutrients.

The following pages give a general idea of the various natural and artificial mineral compounds at our disposal for fertilizer purposes, so that their function may be better understood.

INORGANIC NITROGEN FERTILIZERS

Naturally Occurring Nitrogen Salts

Chile Saltpeter, Sodium Nitrate. The most important of the naturally occurring nitrogen salts is Chile saltpeter. (See page 193.) Chemically, this is mainly sodium nitrate ($NaNO_3$), though the raw product, as mined, also contains as impurities varying amounts of sodium perchlorate ($NaClO_4$), sodium iodate ($NaIO_3$), and sodium periodate ($NaIO_4$), as well as other sodium compounds which are plant poisons. Through special treatment the content of these dangerous impurities must first be reduced to a safe limit. The refined Chile saltpeter, which is sold commercially for fertilizer purposes, contains 15.5 per cent nitrogen. Formerly, this was almost the only available inorganic source of nitrogen, but in recent times Chile saltpeter has been ever-increasingly replaced by synthetically produced sodium nitrate, which contains 16 to 16.4 per cent nitrogen, as well as by various other artificially manufactured nitrogen compounds, discussed below.[1]

Bengal saltpeter, also called niter or potassium nitrate (KNO_3), is mined especially in India, where it occurs naturally, but only relatively small amounts of it (10,000 to 25,000 tons annually) are exported. (See also pages 193 and 216.)

Artificially (Synthetically) Produced Nitrogen Salts

The realization that nitrogen is one of the most important of all plant nutrient substances and that natural supplies are insufficient to fill the ever-increasing demand has resulted in the development of an extensive industry which is occupied with the artificial production of nitrogen fertilizers.

The sources used by this industry are, first, the inexhaustible amounts of elemental nitrogen contained in the air, and, second, the nitrogen compounds of organic origin contained in coal. The various methods employed in the exploitation of these two sources are summarized in the following paragraphs.

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[1] The content in Chile saltpeter of various minor elements, especially of boron, must be considered as significant. Comparative experiments with Chilean nitrate and synthetic nitrate, carried out in Belgium, have consistently produced much superior results with the former. [Baeyens, J., *Plant and Soil,* I., pp. 135–144 (1949).]

NITROGEN FROM AIR

The Electric Arc Process

As early as 1870, Cavendish discovered that electric discharges were capable of causing elemental nitrogen to combine with oxygen and to form nitrogen oxide, though practical application of this discovery was delayed until the beginning of the twentieth century. The process which then was developed—the electric-arc process—in which a temperature of approximately 3000°C (6000°F) is created, results in the production of nitric acid. Unfortunately, the combination of great heat and strong acid, unavoidably involved in this process, presents considerable difficulties and renders very expensive the construction of suitable manufacturing plants. The extremely large amounts of electric power required add still further to the expense and make this process—except possibly in Norway where hydroelectric power is comparatively cheap—unable to compete with other much less costly procedures. The patented "Wisconsin thermal process of nitrogen fixation," which avoids the development of very high temperatures, seems to represent an important step forward in the perfection of the electric-arc process, making a future wider application possible.

Nitrogen Fixation by Means of Catalysts

The process which at present is most commonly exploited industrially is the one invented by Haber and later improved by others, employing catalysts (see page 78) in a direct synthesis of ammonia from elemental nitrogen and hydrogen. The principle of the procedure consists in conducting a mixture of 3 parts per volume of hydrogen plus 1 part per volume of nitrogen (under pressure and at a high temperature) over the catalyst (Haber employed a specially prepared metallic iron) which results in combining the two elements according to the following equation: $N_2 + 3H_2 = 2NH_3$.

By removing the ammonia as it is formed, and by steadily adding hydrogen and nitrogen in the proper proportion, this process is made continuous and goes on without interruption.

The anhydrous (gaseous) ammonia (NH_3) obtained in this manner may either be used in that form or may be converted into ammonium and its salts. Through oxidation, it may be converted into nitric acid and its salts.

Most of the artificial nitrogen compounds manufactured from air nitrogen are produced by means of this process or one of its numerous modifications. In the southwestern parts of the United States, natural gas is now used rather extensively as hydrogen source in this process.

Cyanamide Process. Still another process employed in fixing the nitrogen of the air, and differing considerably from all others, is the so-called cyanamide process, developed by Caro and Frank (1895). The raw material used in this case is calcium carbide (CaC_2) which, when mixed with water, produces the highly inflammable acetylene gas. The finely ground calcium carbide is heated in special electric furnaces to approximately 1000°C (1830°F), and elemental nitrogen then is conducted over it. The combination of the two results in the formation of calcium cyanamide, as illustrated by the following equation:

$$\underset{\substack{\textit{calcium}\\ \textit{carbide}}}{CaC_2} + \underset{\textit{nitrogen}}{N_2} = \underset{\substack{\textit{calcium}\\ \textit{cyanamide}}}{CaCN_2} + \underset{\textit{carbon}}{C}$$

Sprinkling with water, removes the residual calcium carbide and the resulting product contains approximately 60 per cent calicum cyanamide (or 20 to 22 per cent nitrogen).

CALCIUM CYANAMIDE AS FERTILIZER. Calcium cyanamide may be employed directly as a fertilizer, but the evolution of calcium hydroxide which accompanies its transformation in the soil, makes application to alkaline soils inadvisable. Under all circumstances one should realize that calcium cyanamide, as such, is a plant poison, becoming a fertilizer only after its chemical conversion to urea, and then to ammonium. Therefore, it must be incorporated in the soil some time previous to sowing or planting. Application to growing plants—such as corn, for which it is sometimes recommended—must proceed with due caution and at a safe distance from the plants. The speed with which the toxicity disappears depends upon the temperature and the moisture content of the soil as well as on the amount of calcium cyanamide which has been applied. 50 to 80 lb/acre (60 to 90 kg/hectare) are considered to be favorable amounts. During the summer months, and provided that the soil is reasonably moist as well as below neutral in pH value, toxicity is likely to have disappeared within 2 days after application, but for safety's sake it is advisable to allow 2 to 3 weeks before sowing or planting.

TRANSFORMATION OF CALCIUM CYANAMIDE IN SOIL. When incorporated into soil, calcium cyanamide is first hydrolyzed into cyanamide and calcium hydroxide, and the cyanamide is subsequently hydrolyzed into urea. According to recent investigations,[2] this is a purely physicochemical process in which microorganisms take no part. The microorganisms, however, hydrolyze the urea into ammonium carbonate, and nitrifying bacteria then complete the mineralization process. (See page 113.) At a

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[2] Temme, J., *Plant and Soil*, I, pp. 145–165 (1949).

temperature of 23°C (73°F), 50 to 70 lb of calcium cyanamide/acre were completely nitrified within 3 to 4 weeks.

CALCIUM CYANAMIDE AS WEED KILLER. In North America calcium cyanamide has never become popular as a fertilizer, and even in Europe, where formerly fairly large amounts were used, it is now employed in agriculture mainly as a weed killer. In this role its residual action as a nitrogen fertilizer is distinctly welcome, but freshness of the material, which must be kept dry before use and should never be stored for long periods, is very important. When calcium cyanamide is to serve both as weed killer and as fertilizer, it is important not to leave it on top of the soil for more than 2 or 3 days before it is plowed under. Most of this material now is further processed to convert the nitrogen it contains into ammonia and nitric acid. The largest plant on the American continent occupied with the production of calcium cyanamide is located at Niagara Falls, Canada, where ammonium nitrate as well as urea are produced.

Ammonium Nitrate. The salt which combines the ammonium cation with the nitrate anion, called *ammonium nitrate,* was hardly known as a fertilizer 30 years ago but is coming ever more into prominence.

The pure salt, which contains 33 per cent nitrogen—half ammonium and half nitrate—is produced in most factories engaged in fixing atmospheric nitrogen, no matter what method may be employed for this purpose. The principle of the procedure consists in passing anhydrous (gaseous) ammonia through nitric acid. Originally, this material was produced as a step in the manufacture of explosives, and it may itself actually explode under certain not as yet completely understood conditions. This fact renders transport as well as storage of the pure salt hazardous. Besides, ammonium nitrate is rather highly hygroscopic—which means that it greedily takes on moisture from the atmosphere. This may result in its caking together into hard lumps or even into one hard solid mass while in storage.

MIXTURES OF AMMONIUM NITRATE AND OTHER SUBSTANCES. To overcome these two highly undesirable traits, ammonium nitrate is, for fertilizer purposes, now generally mixed with gypsum or with calcium carbonate in some form or other, such as ground limestone, ground dolomite, or ground chalk. Kaolin and other forms of clay may be used also. For use in humid regions ammonium nitrate sometimes is specially treated with paraffin in combination with other substances which renders it at least partly water repellent.

Mixtures of ammonium nitrate with calcium carbonate are particularly useful, because this results at the same time in neutralizing the inherent acidity of this salt. Products of this nature are the American "Cal-Nitro" and "A-N-L" (ammonium nitrate-lime), which contain approximately 10.25 per cent ammonium nitrogen, 10.25 per cent nitrate nitrogen, 9 per cent calcium oxide (CaO), and 7 per cent magnesium oxide (MgO). The English counterpart, "nitro-chalk," contains from 10 to 15 per cent nitrogen.

Of special interest is the double salt ammonium sulfate-nitrate, which in Germany is called *Leuna salpeter*—after the nitrogen fixation plant at Leuna, Germany, which produces it—and in France *sulfo-nitrate d'ammoniaque.* It is produced by mixing solid ammonium nitrate with solid ammonium sulfate, in the presence of a carefully calculated small amount of water and with the addition of small amounts of certain magnesium salts. In consequence of the ammonium sulfate being employed in surplus amounts, the total nitrogen contained in the end product, which is approximately 26 per cent, is composed of about three quarters ammonium nitrogen and one quarter nitrate nitrogen.

This material, therefore, is a high-quality nitrogen fertilizer of particularly desirable composition and may be employed at any time of the year. Since it contains no free ammonium nitrate, it is absolutely safe against explosion. Its acid reaction in the soil must be counteracted by liming. (See Table 31.3, page 338.)

NITROGEN FROM COAL

As explained in Chapter 24, coal deposits originally resulted from organic matter which became deeply buried. In consequence, this material contains a certain amount of complex organic nitrogen compounds. How much nitrogen is present depends upon the age and the type of the coal deposit, brown coal (lignite) and soft (bituminous) coal being richer in nitrogen than hard coal (anthracite).

When coal is coked—which means turned into coke by heating it under the exclusion of air, somewhat on the same principle as charcoal burning—various gaseous substances escape. These include hydrogen, methane, carbon dioxide, ethylene, nitrogen, ammonia, sulfur, cyanogen, etc., as well as condensable vapors, such as steam, benzol and its homologues, naphthalene, carbon disulfide, and tar. In cooling, the condensing vapors separate into two layers, representing the tar and the gas water. From the latter the ammonia is separated through a special process of distillation, after calcium hydroxide has been added.

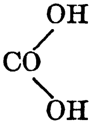
AMMONIUM SULFATE. The agriculturally most important ammonium salt produced in this manner is ammonium sulfate. Amounts of 4.5 to 7.8 lb of anhydrous ammonia or 18 to 30 lb of ammonium sulfate may be obtained from 1 ton of coal, depending upon the nitrogen content of the latter.

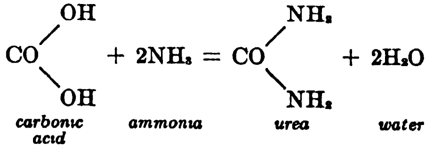
Ammonium sulfate is the oldest of all artificially produced nitrogen fertilizers and has been in use for over 70 years. Larger amounts of this salt are produced and used all over the world, even at present, than of any other artificial nitrogen fertilizer. Most of it results as a by-product of coking, as mentioned above, but some is produced also in factories which utilize the nitrogen of the air.

AMMONIUM PHOSPHATE. Ammonium phosphate is manufactured from ammonia obtained as a by-product of coking. A mixture of several ammonium phosphates (monobasic and dibasic), containing gypsum or sand as filler, is sold commercially under the trade name "Ammo-phos."

Synthetic Urea. Most of the nitrogen contained in the urine of man and other mammals is present in the form of urea, which is a natural organic substance representing the end product of protein digestion. Urea can also be produced synthetically, however, and such artificial urea is identical with the natural product.

Of historical interest is the fact that the artificial synthesis of urea, carried out by Wöhler in 1828 from cyanic acid and ammonia, represents the first instance of synthetic production of an organic substance normally resulting from animal metabolism. This achievement abolished forever the firmly established doctrine that such natural substances could not be duplicated by artificial means.

SYNTHESIS OF UREA FROM CARBONIC ACID OR CARBON DIOXIDE AND AMMONIA. The origin of urea from a combination of carbonic acid with ammonia may be illustrated by means of the following equation. Carbonic acid (H_2CO_3) may be visualized as consisting of two OH groups attached to one CO group as follows:  $CO\genfrac{}{}{0pt}{}{\diagup OH}{\diagdown OH}$. If, to this, ammonia (NH_3) is added, the following results:



$$\underset{\text{carbonic acid}}{CO\genfrac{}{}{0pt}{}{\diagup OH}{\diagdown OH}} + \underset{\text{ammonia}}{2NH_3} = \underset{\text{urea}}{CO\genfrac{}{}{0pt}{}{\diagup NH_2}{\diagdown NH_2}} + \underset{\text{water}}{2H_2O}$$

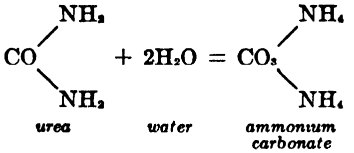
A compound which contains two amido groups (NH_2) attached to an acid radical is called a *diamide*, and urea, therefore, is the diamide of carbonic acid.

Most of the commonly employed procedures for the synthetic production of urea are based on the one developed by Bosch and Meiser, in which ammonia and carbon dioxide, in the presence of water vapor, are subjected to high temperature (approximately 140°C) (284°F) as well as to pressure. This causes them to combine and to form ammonium carbamate ($CONH_2 \cdot ONH_4$). Through the removal of water (H_2O) the latter then is converted into urea ($CONH_2NH_2$).

Urea may be produced also by treating the previously described calcium cyanamide with diluted carbonic acid.

Very large amounts of urea are now produced for fertilizer purposes, and this industry is likely to expand still further in the future.

ACTION OF UREA WHEN ADDED TO SOIL. The conversion of urea in the soil is decisive for its fertilizer action and deserves further explanation. The first step is rapid solution of the urea in water and the second, dependent on the influence of enzymes produced by numerous soil microorganisms, is the synthesis of ammonium carbonate. The latter proceeds according to the following equation:



$$\underset{\text{urea}}{\mathrm{CO}\begin{matrix}\diagup \mathrm{NH_2} \\ \diagdown \mathrm{NH_2}\end{matrix}} + \underset{\text{water}}{2\mathrm{H_2O}} = \underset{\text{ammonium carbonate}}{\mathrm{CO_3}\begin{matrix}\diagup \mathrm{NH_4} \\ \diagdown \mathrm{NH_4}\end{matrix}}$$

Nitrifying bacteria next take a hand and convert the ammonium carbonate into nitric acid, water, and carbon dioxide, as follows:

$$\underset{\text{ammonium carbonate}}{(NH_4)_2CO_3} + \underset{\text{oxygen}}{4O_2} = \underset{\text{nitric acid}}{2HNO_3} + \underset{\text{water}}{3H_2O} + \underset{\text{carbon dioxide}}{CO_2}$$

It is apparent from the above equation that an application of large amounts of urea will result in considerable acidification if the soil is low in calcium content; when necessary, appropriate amounts of ground limestone must be applied to counteract this effect.

The conversion of urea first to ammonium carbonate, then to nitric acid, and finally to nitrate takes, under average conditions, approximately 3 to 4 weeks. Urea, therefore, would actually be an ideal nitrogen fertilizer if it were not for its very high water solubility which renders it subject to loss through leaching.[3]

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[3] Evidence is accumulating that at least certain higher plants are able to absorb the intact and unchanged urea molecule, either from the soil with their roots or through the leaf surface. Through enzyme action urea then is hydrolized within the plant into various amino acids and may finally be converted into ammonia. Some of the same amino acids which evolve from urea in the living plants, and which frequently are present in soils containing organic matter, can probably also be absorbed directly by certain higher plants. (Bollard, E. G., "Urease, Urea and Ureides in Plants," pp. 304–329 of "Utilization of Nitrogen and Its Compounds," Symposium of the Society of Experimental Biology, Cambridge, England, Cambridge University Press, 1959.)

PROCESSING OF UREA TO REDUCE ITS WATER SOLUBILITY. Various methods have been employed in efforts to prepare urea in such a manner that it dissolves less quickly, with the object not only of reducing leaching losses but also of causing the nitrogen to become available more gradually and over a longer period. One of these procedures consists in coating the urea crystals with an inert material, and the fertilizer sold under the trade name "Uramon" is one of the products of this type. "Agramon" and "Floranid" are trade names of other types of urea fertilizers.

Urea-form. Another process with the same aim combines urea with formaldehyde, and the acid-catalyzed condensation product which results has been given the general or generic name "urea-form." This name covers a whole range of products of the same origin, varying in the amount of readily soluble nitrogen compounds they contain as well as in the speed with which the less-soluble fraction becomes soluble and nitrifies. With some of these products all the nitrogen they contain nitrifies as rapidly as with urea (within 3 to 4 weeks) but with others the same process requires 2 to 3 years. All contain approximately 38 per cent nitrogen, and so far it appears that the formaldehyde in their make-up has no objectionable influence, as might have been feared. It has been conjectured that either the formaldehyde is not liberated as such during the enzymatic hydrolysis of these fertilizers or the soil microorganisms are able to utilize the formaldehyde as fast as it is liberated. At any rate, no trace of formaldehyde could ever be detected in a water extract of soils treated with a urea-formaldehyde compound, and, even when abnormally large amounts of such compounds were applied to a soil, no inhibitory effect on the soil microorganisms could be observed.

URAMITE. Experiments with urea-formaldehyde fertilizers continues, and some of these products have recently become available commercially. The presently most outstanding one has been distinguished under the name "Uramite." Like other fertilizers of this type, it contains approximately 38 per cent nitrogen, and of this amount about 25 per cent is readily soluble, nitrifying within the first month after application. The other 75 per cent consists of so-called water-insoluble nitrogen, of which, however, 55 to 60 per cent becomes soluble and nitrifies within the first 6 months after application to an average soil. As must be expected, the rate and speed of nitrification varies with the type of soil to which the fertilizer is applied as well as with the pH of the soil, the soil content of other plant nutrients, the prevailing temperature over the 6-month period, and undoubtedly, also, with the type of crop plant being cultivated. The development of this valuable fertilizer undoubtedly represents only a beginning and can be expected to lead to still further progress in the long search for the ideal synthetic nitrogen carrier. The attributes of such an ideal fertilizer—approached for the first time by "Uramite"—must be the following: It must permit application of large amounts before sowing but must be so constituted that the nitrogen it supplies becomes available gradually and at a steady rate throughout the growing season.

Free Ammonia as Fertilizer

Ammonia Gas and Ammonia Solutions as Fertilizers. Attempts to use aqueous solutions of ammonia or even gaseous ammonia (anhydrous ammonia) instead of ammonium salts were first made in 1930 and aroused considerable interest because of the advantages of such a procedure. By introducing ammonia into the soil by itself, the necessity of adding at the same time the anion of its salt is eliminated. Even in this procedure, though, residual acidity develops which, in a more or less acid soil, must be neutralized with calcium carbonate. (See Table 31.3.)

APPLICATION OF ANHYDROUS AMMONIA. Ammonia has a stifling odor and may cause severe burns on the skin. The eyes and the mouth, especially, must be protected. Proper equipment and caution in handling are necessary to avert this danger. At atmospheric pressure and at a temperature above 28°F ammonia is a gas; below this temperature it is a liquid. Under pressure it also becomes a liquid, and it is shipped under high pressure, usually in tank cars containing 10,000 gal. The liquid weighs 5 lb/gal, and each gallon contains 4.1 lb of nitrogen. Application to the field is made from a pressure tank mounted on a farm trailer and holding 60 to 100 gal. This amount is sufficient to supply 40 lb/acre of nitrogen to from 5 to 9 acres. Since liquid ammonia must be purchased in bulk to be economical, the farmer will need, in addition, a 1,000-gal reserve tank mounted on a four-wheel farm trailer from which to refill his 100-gal tank.

On leaving the tank and therewith being released from pressure, the ammonia turns into a heavy gas; for this reason it must be inserted deeply enough to permit immediate coverage, preventing losses to the air. Equipment is available to take care of this requirement. Soil moisture then dissolves the gas, and thereafter it behaves in the same manner as a dissolved ammonium salt, such as ammonium sulfate.

Anhydrous ammonia may be applied to a seedbed before planting, at planting time, as a side dressing for corn, or, with slight modification, at the time of plowing. No completely satisfactory method has been developed so far that permits spring application for wheat, but, on certain heavy soils, fall application seems to be feasible. On well-drained, sandy soils, subject to leaching, side dressing is preferable to application at sowing time.

Ammonia solutions are employed commonly in mixed liquid fertilizers (see page 325), and frequently are added directly to the soil in irrigation water. In 1949 some 69,000 tons of aqueous ammonia were applied in this manner. Actually, this is by far the cheapest source of ammonia, costing less than half of what ammonia costs in sulfate or in urea. Ammonia in organic forms (as fish meal, tankage, dried blood, or cottonseed meal) costs eight to nine times as much.

Comparison of Nitrate and Ammonium Fertilizers

For guidance in practical application, it may once more be stated that nitrate becomes available immediately but, not being adsorbed by the soil colloids, is easily lost through leaching. Ammonium, on the other hand, which, for instance, in ammonium sulfate is equally soluble, is rather strongly adsorbed by the soil colloids and therefore is not much subject to leaching. Since, in the soil, nitrifying bacteria gradually convert it into nitrate, it is effective over a much longer period. (See also Chapter 18.)

In consequence, nitrate fertilizers should be considered as in the nature of "a shot in the arm," being of short duration, and should by preference be applied as a side dressing during the growing season or as a supplement in early spring, when the nitrifying bacteria are not yet very active. Ammonium fertilizers may be applied at any time, even in fall. That ammonium sulfate acidifies the soil and must be counterbalanced with lime (powdered limestone) may once more be emphasized. (See Table 31.3 for amounts of lime required.) Actually, the swing in the use of nitrogen fertilizers is now ever more and more to ammonia and its salts, which, in the United States at least, make up approximately 80 per cent of all the nitrogen fertilizers employed.

INORGANIC PHOSPHORUS FERTILIZERS

Naturally Occurring Inorganic Phosphorus Compounds as Fertilizer

The origin and distribution of the naturally occurring phosphate minerals—phosphate rock (phosphorite) and apatite—were described and explained in Chapter 19.

Phosphate Rock (Phosphorite). Apatite is employed in Europe for the production of superphosphate, but phosphate rock remains the main source of phosphate, especially in North America. Because the latter material, in its raw state, is sometimes recommended as being preferable to superphosphate, further information on its composition and its behavior when added to soil will be of value. Actually, only a comparatively small amount of phosphate rock is ground and used directly as fertilizer. Most of it (over 90 per cent) is processed further and turned into various types of superphosphate.

COMPOSITION AND DISADVANTAGES OF PHOSPHATE ROCK. The main disadvantage of phosphate rock is that its general composition as well as its content of phosphorus (P_2O_5) varies widely in different deposits. Table 27.1 gives the average composition (in percentages) of some of the best-known types of phosphate rock. The empty spaces signify that the respective figures were not available.

TABLE 27.1. AVERAGE COMPOSITION OF DIFFERENT TYPES OF PHOSPHATE ROCK, IN PERCENTAGES

Phosphate mineral	P_2O_5	CaO	Fe	F	SiO_2
Tennessee brown rock	31.5	44.0	3.4	3.6	10.1
Florida land pebble	35.5	49.7	0.6	3.9	7.5
South Carolina	33.0	39.1	0.7		
Wyoming	32.0	45.3	0.3	3.5	
Utah	32.0	47.0	0.1		
Idaho	35.5	49.0	0.2	3.5	
Montana	32.0	47.0	0.3		
North Africa (Morocco)	41.5		1.0	3.8	
Russia	41.5				
Christmas Island	47.0				
Gilbert Island	48.0		0.4	2.0	
Angaus Island	44.0				

Besides the components listed in Table 27.1, phosphate rock also contains varying amounts of carbonate, sulfate, manganese, and aluminum. The frequently made statement that the fluorine content of phosphate rock is potentially dangerous appears to be completely unfounded. As stated in Part I (see page 24), numerous investigations in various countries have shown that fluorine is not very readily absorbed by plants, and, in fact, no cases of harmful effects produced through the application of fluorine-containing phosphates are known. The highest fluorine content found in various fodder crops, fertilized with phosphates over a period of years, was 2 mg/kg of hay. Cows may be fed as much as 1,000 mg of fluorine per day without injury to their health.[4] Tennessee brown rock,

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[4] Phillips, P. H., Hart, E. B., and Bohstedt, G., *Wisconsin Univ. Agr. Expt. Sta. Bull. No. 430* (1933–34).

which is most commonly employed in the raw state, contains—contrary to occasional claims—quite as much fluorine as most other types, yet no complaints have ever been made that injury to plants, men, or animals has resulted from its use. The only actual disadvantage of the fluorine content is that it lowers phosphorus availability, and this is the reason for the production of the so-called defluorinated phosphates mentioned on page 308.

One further disadvantage which must be mentioned is the fact that most phosphate rocks are extremely hard, making it impossible to grind them as fine as would be desirable for the best effect. An exception is Tennessee brown rock, which is crumbly and is easily reduced to a fine powder.

On the other hand, the price of ground phosphate rock is only about half that of superphosphate, and the former contains nearly twice as much phosphorus (as P_2O_5). These facts are frequently quoted in attempts to prove that phosphate rock is much more economical than superphosphate. Actually, this is not the case, because the analysis giving total phosphorus content disregards the type of phosphate in which the phosphorus is present, though this is decisive for the solubility and, therewith, availability of the phosphorus. It is evident that nothing is gained by adding relatively large amounts of phosphate to the soil when none, or only very little of it, can be utilized by the plants.

ADVANTAGES OF PHOSPHATE ROCK. All of the phosphoric acid contained in phosphate rock is in the form of tricalcium phosphate [$Ca_3(PO_4)_2$] which, at a pH above neutral, is and remains almost insoluble in water. Consequently, it is useless to apply phosphate rock to alkaline soils. With acid soils or soils with a pH below 6, the situation is somewhat different, since under such conditions the tricalcium phosphate is gradually converted into the diphosphate, which is available to plants. (See Chapter 19.) For acid soils, therefore, phosphate rock represents a relatively good source of phosphorus, as long as liming does not become necessary. This once again would render the phosphate insoluble.

Most effective is the application of phosphate rock to soils which not only have a pH below neutral but which also are rich in organic matter. The presence of ammonium, evolved by organic matter, increases the solubility of calcium salts. (See Chapter 21.) For the same reason, it is advisable to apply ammonium salts, such as ammonium sulfate or ammonium nitrate, when phosphate rock is used on a largely inorganic soil.

The increased solubility of calcium salts in the presence of ammonium salts explains why phosphate rock is rather effective when added to manure or compost piles.

ARTIFICIAL PHOSPHATE FERTILIZERS

The artificial phosphate fertilizers may be divided into two groups, depending on whether their official analysis for phosphoric acid content is based on water solubility or on citric acid solubility.

Water-Soluble Phosphate

Superphosphate. Superphosphate, obtained by treating ground phosphate rock with sulfuric acid, is the most important one of the first group. The result of the sulfuric acid treatment is conversion of the insoluble tricalcium phosphate $Ca_3(PO_4)_2$ into the readily water-soluble monocalcium phosphate $[Ca(H_2PO_4)_2]$—according to the following equation:

$$\underset{\text{tricalcium phosphate}}{Ca_3(PO_4)_2} + \underset{\text{sulfuric acid}}{2H_2SO_4} + \underset{\text{water}}{5H_2O} = \underset{\text{monocalcium phosphate}}{Ca(H_2PO_4)\cdot H_2O} + \underset{\text{calcium sulfate}}{2(CaSO_4\cdot 2H_2O)}$$

When superphosphate is stored in rooms which are not absolutely dry, a certain loss in water solubility may occur, especially when the superphosphate contains 3 or more per cent of iron or aluminum compounds. What happens then is that some of the triphosphate still present reacts with the monophosphate and forms diphosphate, according to the following equation:

$$\underset{\text{tricalcium phosphate}}{Ca_3(PO_4)_2} + \underset{\text{monocalcium phosphate}}{Ca(H_2PO_4)_2} + \underset{\text{water}}{8H_2O} = \underset{\text{dicalcium phosphate}}{4(CaHPO_4\cdot 2H_2O)}$$

In other words, a part of the water-soluble phosphate has been converted into citric acid-soluble phosphate. Since in the soil monocalcium phosphate is converted rather quickly into the diphosphate (see page 209), this retrogression is not nearly as important as it was formerly believed to be.

COMPOSITION OF SUPERPHOSPHATE. Commercial superphosphate is a grayish granular powder with a content of 15 to 25 per cent P_2O_5, phosphorus pentoxide (6.5 to 11 per cent P, phosphorus). In general, one can count on 20 per cent P_2O_5 (8.6 per cent P). The average composition of the whole compound may be given as follows: 50 per cent calcium sulfate or gypsum $(CaSO_4\cdot 2H_2O)$; 27 per cent monocalcium phosphate $[Ca(H_2PO_4)_2]$; 2 to 3 per cent dicalcium phosphate $[Ca(HPO_4)\cdot 2H_2O]$; 2 per cent tricalcium phosphate $[Ca(PO_4)_2]$; 6 to 9 per cent silica (SiO_2);

2 to 5 per cent iron and aluminum sulfate; 0.5 to 2 per cent calcium fluoride; and 5 to 10 per cent water. This means that superphosphate contains approximately 20 per cent calcium and 12 per cent sulfur as well as various other minerals, a fact which frequently is not realized.

Because superphosphate consists of about 50 per cent gypsum, its phosphoric acid content—though more readily available—is less than that of the original phosphate rock. To increase its content of phosphorus is possible only through reduction of the sulfate fraction by means of replacing sulfuric acid with phosphoric acid. This is entirely feasible and has been carried out successfully, though the economy of the process hinges on methods of producing phosphoric acid cheaply enough.

DOUBLE OR TRIPLE SUPERPHOSPHATE. The most commonly employed procedure consists in treating low-grade phosphate rock with sulfuric acid in such a manner (carefully watching the proportions added) that phosphoric acid and gypsum result according to the following equation:

$$\underset{\substack{\textit{tricalcium}\\\textit{phosphate}}}{Ca_3(PO_4)_2} + \underset{\substack{\textit{sulfuric}\\\textit{acid}}}{3H_2SO_4} + \underset{\textit{water}}{6H_2O} = \underset{\substack{\textit{phosphoric}\\\textit{acid}}}{2H_3PO_4} + \underset{\textit{gypsum}}{3CaSO_4 \cdot 2H_2O}$$

The difference between this equation and the one given on page 307 is that, in the present case, the amount of sulfate ions supplied must be exactly sufficient to attach all three of the calcium ions of the triphosphate. The gypsum then is removed through filtration, and the phosphoric acid-containing filtrate is brought to a certain desired concentration through evaporation.

Phosphoric acid may be produced also in the electric furnace by subjecting phosphate minerals to high temperature in the presence of coke and sand.

The second step of this process then consists in treating high-grade phosphate minerals with phosphoric acid, which has the following result:

$$\underset{\substack{\textit{tricalcium}\\\textit{phosphate}}}{Ca_3(PO_4)_2} + \underset{\substack{\textit{phosphoric}\\\textit{acid}}}{4H_3PO_4} + \underset{\textit{water}}{3H_2O} = \underset{\substack{\textit{monocalcium}\\\textit{phosphate}}}{3Ca(H_2PO_4)_2 \cdot H_2O}$$

The resulting calcium phosphates, termed in the trade double, triple, or concentrated superphosphate, contain 45 to 50 per cent water-soluble phosphate. Their content of calcium is reduced to approximately 10.5 per cent and of sulfur to 0.8 to 2.5 per cent. Most of these phosphate compounds are employed in the production of high-grade mixed fertilizers.

DEFLUORINATED PHOSPHATES. The so-called defluorinated phosphates, produced, for instance, by the Tennessee Valley Authority (TVA), are obtained by sintering rock phosphate with silicic acid. They consist mainly of "fused" tricalcium phosphate with a content of 20 to 25 per cent phosphorus pentoxide and not more than 0.5 per cent fluorine. The material is stated to have the same fertilizer value as an equal amount of superphosphate (20 per cent).

CALCIUM METAPHOSPHATE. Still another artificial phosphate fertilizer, which likewise is being produced by TVA, may be mentioned here. This is calcium metaphosphate [$Ca(PO_3)_2$], commercially called *metaphos,* which results from a rather complex process combining elemental phosphorus with mineral phosphates. The final product has a total phosphate content of 60 to 63 per cent, though only part of these amounts appears to become available in the soil.

Citric Acid-Soluble Phosphate

Basic Slag. The most important one of those phosphate fertilizers which are judged officially according to their content of citric acid-soluble phosphorus is basic slag. This results as a by-product in the manufacture of steel, where phosphorus has to be removed. Especially in Germany but also in Great Britain and France, where iron ore with a comparatively high phosphorus content is mined, the so-called "basic process" of steel manufacture is employed, which results in a slag of approximately the following composition: 12 to 20 per cent phosphorus (P_2O_5); 40 to 50 per cent calcium (CaO); 5 to 10 per cent silica (SiO_2); 12 to 16 per cent iron (as FeO and Fe_2O_3); 5 to 10 per cent manganese (MnO); and 2 to 3 per cent magnesium (MgO). Ground to a fine powder, this material is sold commercially under the names "Thomas meal," "Thomas phosphate," or "basic slag" and is an excellent fertilizer. The phosphorus it contains is in the form of calcium silico-phosphate ($C_4P_2O_9 \cdot Ca_2SiO_4$), which is much more readily soluble and, therefore available, than the tricalcium phosphate contained in phosphate minerals. Because it acts more slowly than superphosphate, it is best applied in fall or early spring. Its basic reaction, resulting from its high calcium content, renders it of greatest importance for use on all types of acid soil. Its manganese and magnesium content is definitely worth while also. Several million tons of basic slag are produced annually in Europe and represent a very valuable by-product of the steel industry.

According to the rules of the Committee of the American Association of Official Agricultural Chemists, basic phosphate slag must contain a minimum of 12 per cent total phosphorus of which at least 80 per cent must be citric acid soluble. American steel mills generally use only high-grade iron ore with a very low phosphorus content and employ the so-called "acid process" of steel manufacture, which does not result in this type of slag. In consequence, little basic slag is produced in North America (except, for instance, in Alabama).

Artificial Phosphate Slags. Several European countries produce similar slags, specially and solely for fertilizer purposes, by melting or sintering tricalcium phosphate at very high temperature (over 1000°C) with certain alkali salts, such as potassium sulfate, sodium carbonate, silicate, etc. Some of the trade names under which such products are sold commercially are "Rhenania-phosphate" (Germany), "Vesta-phosphate" (Belgium), and "Thermophosphate" (Russia). Compared with superphosphate and even with Thomas meal, these products appear to be of only limited economic importance.

Precipitated Dicalcium Phosphate. The so-called "precipitated dicalcium phosphate," which results as a by-product in glue and gelatin manufacture by heating bones with acid and precipitating the residue with lime, is likewise of very minor importance.

INORGANIC POTASSIUM FERTILIZERS

Naturally Occurring Potassium Salts

Chapter 20 has told how potassium-containing salt deposits resulted from the evaporation of sea water in various parts of the world formerly covered by the sea. Table 27.2 lists the most important of the natural potassium salts occurring in such deposits, together with their chemical formulas and their average content of potassium oxide.

TABLE 27.2. POTASSIUM SALTS WHICH OCCUR IN NATURAL DEPOSITS

Name of mineral	Formula	Potassium oxide content, %
Carnallite	$KCl \cdot MgCl_2 \cdot 6H_2O$	8–15
Kainite	$KCl \cdot MgSO_4 \cdot 3H_2O$	12–20
Sylvinite	KCl with other salts	12–40
Langbeinite	$K_2SO_4 \cdot 2MgSO_4$	18–23
Polyhalite	$K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$	16.6
Leonite	$K_2SO_4 \cdot MgSO_4 \cdot 4H_2O$	20–25
Syngenite	$K_2SO_4 \cdot CaSO_4 \cdot H_2O$	25–30
Kalinite	$K_2SO_4 \cdot Al_2(SO_4)_3 \cdot 24H_2O$	8–10

These minerals never occur in pure deposits, but one or the other usually dominates in a mixture. Carnallite, for instance, usually contains admixtures also of rock salt (NaCl), (3 to 60 per cent); kieserite

($MgSO_4 \cdot H_2O$), (0 to 25 per cent); sylvinite, polyhalite, kainite, etc. The so-called "hartsalz" (hardsalt), the mineral salt conglomerate most commonly mined in Germany, consists of sylvinite (12 to 23 per cent), rock salt (35 to 70 per cent), kieserite (10 to 50 per cent), and varying amounts of langbeinite, kainite, carnallite, etc. Small amounts or traces of boron, bromine, rubidium, ammonium, cesium, and lithium are usually present in such salt deposits also.

In the beginning of the European potash industry—the German deposits were discovered in 1856—rather large amounts of the crude salts (mainly the above-mentioned hartsalz) were ground up and used directly as fertilizer. As was soon realized, the various admixtures this product contained—such as sodium chloride, magnesium chloride, and aluminum—are injurious to plants, and germinating seeds in particular are easily harmed by them. The brilliant and detailed studies of van't Hoff, which showed that the manner in which the various salts were deposited under natural conditions was governed by their dependence on concentration and temperature, opened the way for the production of purified fertilizer salts. As soon as it was understood what conditions had caused these salts to form in the first place, it became possible to separate them again simply by reversing the process. Since these purified salts are much safer to use, they have now largely replaced the natural minerals in practical application. Many of the impurities have now become valuable by-products of the potash industry, a fact which assists materially in keeping down the cost of production and, therewith, the ultimate price of high-grade potassium fertilizers. Some of these by-products are magnesium sulfate, magnesium chloride, sodium sulfate (Glauber's salt), bromine and bromides, borax and boracic acid, lithium salts, etc.

Artificially Produced or Purified Potassium Fertilizers

Muriate of Potash. The potassium salt which is most commonly used for fertilizer purposes, amounting to approximately 90 per cent of the world's total, is potassium chloride, commonly called muriate of potash. The American product contains an average of 53 per cent potassium (as K).

The production of this salt consists mainly in separating it from the various other salts which, together, form a compound mineral. The extraction methods vary somewhat with the type of raw material, but the general principle consists in first grinding the mineral, then dissolving it in hot water (approximately 90°C) containing surplus amounts of magnesium chloride ($MgCl_2$) and finally cooling it gradually in a series of tanks. This causes the individual salts to separate. In practical application the procedure is modified in various ways, most of all by varying the concentration of the solution which, together with the temperature, governs the solubility of the different salts. The potassium chloride obtained in this manner is usually still further refined by washing it with cold water, in order to remove as much as possible of the common salt (NaCl).

The relative simplicity of the procedure renders potassium chloride the cheapest available source of potassium, which undoubtedly contributes to its popularity.

Potassium Sulfate. The most commonly employed procedure in the production of potassium sulfate is to dissolve in water, at a temperature of approximately 50°C, any one of the double sulfates of potassium and magnesium—such as langbeinite or leonite (see Table 27.2)—and to add to this a concentrated solution of potassium chloride. This results in precipitating the potassium sulfate, after which the rest of the solution or the precipitate is removed. The various modifications of this method, which are necessitated by differences in the raw material, cannot be discussed here; the principle, however, remains always very much the same. The fact that potassium chloride has to be produced first and must be employed in the reaction which results in the precipitation of the potassium sulfate is the reason for the higher market price of the latter.

Potassium sulfate is obtained also from the mineral alunite (see page 213) by first roasting the alunite (at about 750°C), which causes it to decompose, and then leaching out the potassium sulfate. This method is employed, for instance, in Utah and Nevada, but, so far, it does not appear to be economical enough to compete with the production of potassium sulfate from other minerals.

Comparison of the Two Most Important Potassium Salts. With most plants it does not appear to make any appreciable difference whether potassium is applied as chloride or as sulfate. There is a certain amount of evidence, however, that potatoes especially may be harmed by large quantities of chloride. It appears that accumulation of chloride in the potato leaves interferes with their photosynthetic activity, resulting in a lowering of the quality of the starch accumulated in the tubers. Beans also seem to be somewhat sensitive to chloride, and tobacco may lose in burning quality when large amounts of potassium chloride are applied to the soil. For these three types of plants, therefore, potassium sulfate is generally recommended. In citrus, peach, and pecan culture, potassium sulfate is preferred also, since these trees appear to be quite sensitive to chloride.

On the other hand, there are ample reports which tend to show that the chloride fraction of potassium chloride is actually beneficial to many other crop plants, for instance, table beets, sugar beets, tomatoes, and spinach. In general, it seems that on acid soils potassium sulfate is somewhat more efficient than the chloride, and that under all circumstances where a serious potassium deficiency exists and it is necessary to apply large amounts, it is safer to apply a mixture of both chloride and sulfate than either one alone. (See page 329 for the probable reason.)

When potassium chloride is used alone, fall application is generally preferred, because winter moisture can be counted on to leach away a large part of the chloride fraction before the spring sowing.

Potassium Silicate. Potassium silicate, with a potassium content of approximately 25 per cent, was formerly manufactured in Germany but does not appear to be available at present. It is mentioned here only because it may have future possibilities.

Potassium Nitrate. Potassium nitrate, which has been discussed in Chapter 20, is manufactured mainly in Germany and is very little used in North America. It has a content of approximately 14 per cent nitrogen and 40 per cent potassium oxide. Its original reaction is neutral, but in the soil it gradually produces alkalinity, and it is said to cause deflocculation of clayey soils if applied repeatedly in large quantities.

Double Salts of Potassium and Magnesium. Some double salts, such as potassium-magnesium sulfate, produced, for instance, in New Mexico from langbeinite (mainly by washing the latter), but also from the brines of Searles Lake, may be mentioned here for the sake of completeness. Potassium-magnesium carbonate, which is being produced in Germany, is somewhat similar in effect, though it has a pronounced alkaline reaction. Both may be of interest where magnesium as well as potassium are required but chloride is not wanted.

Potassium Metaphosphate. Potassium metaphosphate, produced by the TVA, is still in the experimental stage and for the present, at least, is too high in price to be of much interest.

FERTILIZERS SUPPLYING OTHER REQUIRED NUTRIENTS

The other elements which plants require—besides nitrogen, phosphorus, and potassium—are usually considered as of much less importance than these three. Actually, this is erroneous. Calcium, for instance, is just as important for plant nutrition as is potassium, and sulfur readily compares in importance with phosphorus. Certain plants, such as many Leguminosae and some Cruciferae, even contain larger amounts of sulfur than of phosphorus in their tissues. Other elements, such as magnesium, iron, manganese, copper, and boron, are equally indispensable, and, though plants use them in much smaller amounts, a pronounced lack of any one of them becomes quickly apparent by the ill health of the plants.

Minor Elements in Commonly Applied Fertilizers

The main difference between these elements and nitrogen, phosphorus, and potassium, and the main reason why the former are frequently disregarded, is that the average fertile soil contains them all in ample amounts. In addition, a correct fertilizing program directed toward maintaining a satisfactory level of nitrogen, phosphate, potassium, and humus always results in adding to the soil, at the same time, varying amounts of the other elements also. Superphosphate, for instance, as has been shown, adds calcium and sulfur in fairly large amounts. Potassium sulfate and ammonium sulfate likewise add sulfur. When powdered dolomitic limestone is applied to correct soil acidity, magnesium as well as iron, which are present in this material, are added. Furthermore, the various phosphorus and potassium fertilizers are not chemically pure salts and always contain all kinds of other elements which are added to the soil whenever these fertilizers are applied. It was mainly for the purpose of making this fact perfectly clear that the methods employed in manufacturing the various artificial nitrogen-phosphorus-potassium fertilizers were discussed in some detail in the preceding pages.

When humus is applied in any of the previously described types of manure or compost, the addition of the various so-called "minor elements," which these materials unavoidably contain, is actually of much greater importance than the amounts of phosphate and potassium which are added with them.

Causes of Deficiencies

In spite of all this, deficiencies in any one of these elements do occur, resulting from the following four main causes:

(1) Certain submarginal soils, such as peaty soils or very sandy soils, may be naturally deficient in one or even in several of these elements, the latter having been leached out through natural processes during the deposition and development of these soils.

(2) The natural pH value of certain soils, either too high or too low, may prevent one or several of these elements from becoming available to plants, though the elements actually are present in sufficient amounts.

(3) The presence of large surplus amounts of one element—in nature most commonly calcium in highly calcareous soils or sometimes mag-

nesium—may interfere with the absorption and, most of all, with the utilization of certain other elements. (See page 245.) Especially iron and manganese but also boron, zinc, etc. may thus be rendered ineffective or only partly effective, in spite of the fact that they are available in sufficient amounts. Such so-called physiological deficiencies are actually much more common than true deficiencies.

(4) The unskilled interference of man, such as overapplication of one particular type of fertilizer or application by guess of the wrong type of fertilizer—without consideration of soil pH and without previous soil analysis—may have caused any one or several of these elements either to become unavailable or to be leached away. Leaching, especially, may result in very serious trouble.

Effect of Overliming with Hydrated Lime. Amateur gardeners, in particular, are likely to apply hydrated lime to their soil for no other reason than that they have read somewhere that heavy clay can be improved through liming. The likely consequences of such a treatment—especially when the soil pH value was already near neutral or perhaps even more or less alkaline—may be illustrated by the following equation:

$$\underset{\substack{\textit{potassium}\\ \textit{colloid}}}{2\text{K coll}} + \underset{\substack{\textit{calcium}\\ \textit{ion}}}{\text{Ca}^{++}} \rightleftharpoons \underset{\substack{\textit{calcium}\\ \textit{colloid}}}{\text{Ca coll}} + \underset{\substack{\textit{potassium}\\ \textit{ion}}}{2\text{K}^{+}}$$

This means that the surplus calcium ions of the highly soluble hydrated lime will force the potassium ions to leave the soil colloids—by which they were held adsorbed—and to enter the soil solution, while their place on the soil colloids will be taken by the calcium ions. This forcible replacement is, of course, not confined to potassium but affects, in the same manner, all the other cations which may be present, such as the valuable ammonium, magnesium, iron, and manganese. Potassium was singled out merely because, in most instances, it will be present in much larger amounts than any of the others.

Damage will result from the fact that the ions which have been forced off the soil colloids are likely to be lost with the drainage water, which means that the first rain or a thorough irrigation will leach them away and will leave the soil that much poorer in plant nutrient contents.

Overapplication of Potassium. The reversibility of this process is expressed by the two arrows of the above equation, which indicate that the application of overlarge amounts of potassium may in the same manner cause the loss of calcium and magnesium as well as of other cations. This is most likely to happen in greenhouse culture or in truck gardening, where commercial growers frequently apply indiscriminately large amounts of fertilizers without control through analysis.

Overapplication of Gypsum. Application of overlarge amounts of gypsum (calcium sulfate) can likewise cause loss of potassium and other cations. In fact, since gypsum has a relatively high solubility (0.26 per cent), this may happen rather easily, especially in acid or near-neutral soils, where it may not even be accompanied by a change in pH value.

Overapplication of Ammonium Fertilizer. Even the overapplication of ammonium fertilizer may result in at least partial loss of certain other cations, though this danger is never as acute because the ammonium ion is much less aggressive than the potassium ion, and still less than the highly mobile calcium ion of hydrated lime. The application of large amounts of ammonium sulfate is most likely to cause trouble with a more or less acid soil and when the residual acidity of this fertilizer is not compensated through the addition of appropriate amounts of calcium carbonate. The soil contents of iron and manganese will then be endangered merely through an increase in the solubility of the respective compounds, resulting in leaching.

Application of Calcium Carbonate. That calcium carbonate (ground limestone) is not able to cause complete saturation of the soil colloids and, therewith, serious loss of other cations has been explained elsewhere (page 225). When highly acid soils are limed, however, even calcium carbonate should not be applied in amounts of much above 5,000 to 6,000 lb/acre at one time, because, under such conditions, its solubility is bound to be increased considerably through the formation of calcium bicarbonate and calcium sulfate. Though serious losses will remain unlikely, even a partial loss should be avoided.

It is evident from the foregoing that the overapplication of fertilizers is not only wasteful but may actually do considerable harm. Soil analysis offers a ready means of avoiding such costly errors.

Stoichiometric Exchange. The forcible exchange of cations on the colloids, which was discussed above, takes place according to atomic weight in equivalent proportions, or, in scientific terminology, stoichiometrically. This fact is employed in the preparation of extracting solutions used in soil analysis, where a surplus of one cation is introduced deliberately to replace and, thus to extract, another.

Correction of Imbalances of Minor Elements

It is quite impossible to take intelligent steps for the correction of a deficiency or surplus as long as one remains ignorant of what has caused it. For instance, when an element has been leached out because of overapplication or wrong application of another, it must not only be replaced, but one also must avoid making the same mistake in the future. When an element has became unavailable through overalkalinization or overacidification of the soil, the problem is not solved through the addition of more of the unavailable element. The most efficient procedure will be to adjust the soil pH value. That the favorable nutritional balance, which has been mentioned several times previously, can be upset just as readily by the lack of a minor element as by insufficient supplies of one or the other of the major elements should need no further emphasis.

The roles played by the various elements in the lives of plants have been outlined in Part I. It remains only to enumerate the most efficient substances which may be used to correct an imbalance in any one particular element other than nitrogen, phosphorus, and potassium, when soil analysis has established a definite need for remedial action. Calcium and sulfur have been treated in ample detail in Chapters 21 and 22.

Magnesium. A true deficiency of magnesium is most easily corrected through application of powdered dolomitic limestone containing as much as 20 per cent or even more of magnesium carbonate. Under conditions where lime is not required or not wanted, magnesium sulfate, which is obtained from mineral salts as a by-product of the potassium industry, should be used. This material is very cheap and, being neutral in reaction, is perfectly safe as long as it is not applied in overlarge amounts. Under normal conditions an application of 60 to 150 lb/acre of magnesium sulfate or 75 to 150 lb of dolomitic limestone is usually sufficient to correct a pronounced deficiency. If potassium must be applied at the same time, the double salt potassium-magnesium sulfate (page 313) may be used instead.

EPSOM SALT. For completeness' sake it may be mentioned that the well-known purgative Epsom salt, a component of the water of many famed mineral springs, is a hydrated magnesium sulfate ($MgSO_4 \cdot 7H_2O$). It may be used to correct magnesium deficiency in house plants or on a small vegetable plot by watering with a very dilute solution of a few crystals. This must not be done unless soil analysis or observation of the symptoms apparent in the plants has established that a lack of magnesium actually is the cause of the trouble.

MAGNESIUM IN SURPLUS. A very high magnesium content (over 10,000 lb/acre) occurs locally in various parts of the world. This creates very unfavorable conditions for plant growth, because it interferes with the utilization of other cations such as potassium, calcium, iron, and manganese. Frequently, such soils have, at the same time, a rather high potassium level (300 to 600 lb/acre), but it has been reported that, even under such circumstances, a heavy application of potassium sulfate (1,000 lb/acre or more) greatly improves the health and development of the plants. The chances are considerable that ammonium sulfate in doses of no more than 500 lb/acre will be found still more effective as well as less expensive.

Manganese. Most soils contain sufficient manganese to supply the needs of plants, only relatively small amounts being required, but any interference with natural conditions is likely to change availability. Heavy liming of an acid soil and, in particular, sudden raising of the pH above 6.5 through application of calcium hydroxide, may depress the solubility of manganese so far that deficiency symptoms become observable. Even the burning of brush in piles, without scattering of the resulting highly alkaline wood ashes, may create spots where manganese has become unavailable. In such cases the application of sulfur will serve to restore soil pH to a more favorable level. When manganese deficiency is caused by an actual lack of the element resulting from leaching, a correction can be effected through the use of manganese sulfate.[5] Applications of 50 to 100 lb of manganese sulfate are generally sufficient to correct a true deficiency which, by the way, is least likely to develop where manure or compost is applied regularly.

MANGANESE TOXICITY. A surplus of manganese in the soil (much above 100 lb/acre) is dangerous and harmful to plants. This means that if manganese deficiency is suspected, one must first make sure, by soil analysis, that this is actually the case before adding manganese sulfate to the soil. Natural manganese toxicity may occur in certain more or less acid lateritic soils—for instance in the pineapple-growing regions of Hawaii—but occasionally it is found also in highly organic soils with a pH below 5. Carefully calculated applications of calcium carbonate (ground limestone) will usually help by reducing manganese solubility to a safe limit.

Iron. A true deficiency of iron is relatively rare, since the average soil contains rather large amounts. The conditions which influence the availability of manganese, however, may also cause iron to become unavailable. One safe way to add iron to a soil which lacks it is to apply basic slag which, at the same time, serves as an efficient phosphorus fertilizer. (See page 309.) In the Hawaiian pineapple fields where a high soil content of manganese interferes with iron availability, a 5 per cent solution of ferrous sulfate, applied as a spray to the leaves at the rate of 50 to 100 gal/acre/week, has been found to be very effective.[6]

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[5] According to recent investigations, finely ground manganite [MnO(OH)] appears to be more satisfactory as well as more lasting, especially on alkaline soils, in relieving manganese deficiency, than is manganese sulfate.

[6] Spraying with a 2.7 per cent solution of ferrous ammonium sulfate has been found most satisfactory elsewhere.

IRON CHELATE AND "FRITTED" TRACE ELEMENTS. Iron chelate (called also chelated iron or, in England, iron sequestrol or sequestrene iron) has lately come into horticultural prominence. The chelates or sequestrenes are organic compounds—based on ethylenediamine tetraacetic acid—in which metallic elements are included in such a manner that they cannot react chemically in their normal fashion. They are "chelated," which means "clawed or gripped." The English name "sequestrene" was developed from "sequestrated," meaning "held apart or in isolation." The advantage of the chelates is that the metallic elements they contain remain available to plants in spite of the fact that they are rendered inactive chemically. In other words, the chelates, or "fritted trace elements," offer an opportunity to supply iron and other metallic elements, such as manganese, magnesium, copper, zinc, and aluminum, in such a manner that excess of lime or of phosphates cannot adversely influence their availability to the plants. There is still much to be learned about the proper use of chelates in horticulture—one observation indicates, for instance, that a favorable level of nitrogen in readily available form is important for full utilization of chelates—but little doubt remains that eventually these chelates will assume considerable importance in fruit and vegetable culture.

Boron. The average soil with a pH near the neutral point is usually well supplied with boron as far as the needs of most plants are concerned, but danger of loss of this element by drainage is always present. The soil colloids adsorb only small amounts of boron, and especially sandy soils low in organic matter are much exposed to boron loss through leaching. At a pH level above 7.5, boron, like manganese and iron, becomes unavailable. Quite a number of minerals occurring in the soil contain traces of boron, but the most common source is tourmaline, $M_{20}B_2Si_2O_2$ (the M standing for any one of several bases, such as iron, aluminum, magnesium, manganese, calcium, and potassium). Though this mineral is never present in large amounts and its solubility is very low, it must be held largely responsible for the maintenance of soil boron supplies. The presence of organic matter increases the solubility of tourmaline and, therewith, the availability of boron, while at the same time organic matter itself contains organic boron compounds.

BORON DEFICIENCY. Under most circumstances proper soil treatment, such as control of soil pH and application of organic matter, can assure the availability of sufficient amounts of boron without the necessity of adding any to the soil. Continuous intensive cropping, however, especially when the crop is entirely removed at harvest, can easily result in exhaustion of the available boron, because the boron-bearing minerals which are present dissolve so slowly that they cannot replace supplies quickly enough, and thus the loss becomes cumulative. This suggests that the widespread practice of one-crop culture, not sufficiently relieved by pasture rotation, is largely to blame for the increasingly observed boron deficiency in many parts of the world.

The boron requirement of plants increases with their calcium content, which is always highest on calcium-rich soils. This means that where boron supplies are critical one must avoid the application of large amounts of calcium even in the form of calcium carbonate, since this in itself, and regardless of soil pH, may cause boron deficiency. It means also that, in the presence of calcium, plants can stand higher concentrations of boron without injury, and this explains why, in cases of soil boron toxicity, the application of calcium carbonate is the most effective countermeasure. The calcium carbonate, at the same time, will raise the pH of the soil, thus rendering boron less soluble.

BORON REQUIREMENTS OF PLANTS. Considerable work has been done on establishing the boron requirements of different types of plants; the findings may be summarized as follows:

Plants having the highest requirement (0.5 ppm or 1 lb/acre) are the various clovers, as well as alfalfa, beets, turnips, mangolds and radishes, cabbage and its relatives (such as cauliflower, etc.), celery, asparagus, sunflower, and apple.

Medium requirements (0.1 to 0.5 ppm or 0.2 to 1 lb/acre) apply to tomato, tobacco, lettuce, onion, sweet potato, and carrot, as well as various fruit trees (except apple), nut trees, cotton, and peanuts.

A low requirement (0.1 ppm or 0.2 lb/acre) is typical for various grasses and grain crops, as well as beans, peas, white potato, flax, strawberry, raspberry, and citrus fruits.

CORRECTING BORON DEFICIENCY. The material most commonly employed to relieve a true boron deficiency is borax, sodium tetraborate ($Na_2B_4O_7 \cdot 10H_2O$), which is applied in amounts of 5 to 50 lb/acre. One should bear in mind, however, that many mixed fertilizers contain borax (0.01 to 0.2 per cent), which, as required by law, is stated in their analysis. Since overapplication of borax may cause boron toxicity, this material must be used only on the advice of a competent authority.

Copper and Zinc. Copper and zinc may be mentioned together because they have much in common. Both are usually present in the soil in sufficient quantity and are required by plants only in very small amounts. Their various compounds are highly soluble, whenever ammonium is present, which is the case nearly everywhere. In consequence, no type of soil is safe against the leaching out of these elements, wherever rainfall is sufficient to produce leaching. (See pages 108 and 254.) The small amounts of copper and zinc which are present in the soil in available form can be determined only in a fully equipped laboratory, and even then it is extremely difficult to arrive at a proper interpretation of the analysis. Fortunately, the symptoms produced in plants by copper or zinc deficiency are well known and readily recognizable. The best procedure, therefore, when a deficiency in either of these elements is suspected, is to consult a plant pathologist.

CORRECTION OF COPPER DEFICIENCY. A true copper deficiency may be corrected through the application of 50 to 75 lb/acre of copper sulfate which is most effective as a liquid spray over the soil surface before plowing. Twice and even three times these amounts have sometimes been recommended, but such large amounts should never be applied without first establishing the soil pH value. The reason is that under acid conditions copper sulfate, which itself has a pH of about 3, is 100 per cent soluble and may not only cause temporary toxicity but, especially in a sandy soil, may be leached out in a very short time. When soil pH is below 6, one should add powdered limestone, so as to raise the pH to slightly above 6. This will result in making at first only a little of the copper sulfate soluble, and thus available. Since one application of ground limestone cannot permanently neutralize a naturally acid soil, the pH value is bound to drop again, and more and more of the copper sulfate will gradually become available as the acidity increases.

One difficulty with copper sulfate is that, in soils of relatively high pH value (even near the neutral point), it may produce or increase manganese and iron deficiency, possibly by acting as a catalyst in the oxidation of manganese and iron. In addition, copper sulfate is rather expensive. Recent experiments carried out in Denmark[7] suggest that finely ground copper pyrites or cupric oxide (ashes of sulfur and copper pyrites) or malachite may offer promising possibilities. Though more slowly effective, their action is sustained over a longer period, application is easier (500 to 600 lb may be spread over each acre instead of only 50 lb), and the price is much lower (one half to one third).

CORRECTION OF ZINC DEFICIENCY. A true zinc deficiency is most likely to occur under conditions of high insolation and high summer temperature. In orchards of fruit or nut trees it is sometimes corrected through the application of ½ lb of dry zinc sulfate, spread around each tree which shows a deficiency. Since zinc sulfate, which likewise has a very

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[7] Steenbjerg, F., and Boken, E., Plant and Soil, II, p. 195, 1950.

Childers, N. F. (editor) and 27 others. Mineral Nutrition of Fruit Crops. 907 pages. Horticultural Publications, Rutgers University, New Brunswick, N.J., 1954.

low pH value (pH 4), behaves in the soil in very much the same manner as copper sulfate, the same caution is required as was outlined for copper deficiency. (See also page 321.)

In general, it has been found to be safer and more satisfactory to apply zinc to the leaves of plants in the form of a spray, consisting of 1 lb of zinc sulfate dissolved in 50 gal of water, three or four times during the growing season. The main disadvantage of this procedure is that it has to be repeated every year.

28. MIXED FERTILIZERS

Under this heading must be mentioned first of all those fertilizer salts which, because of their chemical composition, supply more than one important nutrient substance at the same time. As was explained in Part II (page 73), a salt is a combination of a cation with an anion. Therefore, all salts contain, besides the cation or anion which we may wish to add to the soil, also a cation or an anion which unavoidably is added with it. The only fertilizer salt which adds only one element in both cation and anion form is ammonium nitrate (see page 298), supplying only nitrogen. Naturally, it is much more economical as well as simpler in application when, for instance, potassium as well as nitrate can be supplied by means of a single compound containing both, instead of in two separate compounds. This is the advantage of potassium nitrate. The same applies to ammonium phosphate ("Ammo-phos") as well as to potassium orthophosphate (K_3PO_4) and potassium metaphosphate [$K_4(PO_2)_4 \cdot 2H_2O$]. The three last-named products are employed particularly in the preparation of high-grade mixed fertilizers.

Ammoniated Superphosphate

Much longer in use—since 1928—are the so-called ammoniated superphosphates, which are prepared through treatment of superphosphate with an ammonium solution or with anhydrous ammonia. This results in the reaction illustrated by the following equation:

$$\underset{\substack{\textit{monocalcium}\\ \textit{phosphate}}}{Ca(H_2PO_4)_2} + \underset{\textit{ammonia}}{NH_3} = \underset{\substack{\textit{dicalcium}\\ \textit{phosphate}}}{CaHPO_4} + \underset{\substack{\textit{ammonium}\\ \textit{monophosphate}}}{(NH_4)H_2PO_4}$$

When a surplus of ammonia is applied (over 2.5 per cent), this treatment may result also in other reactions, and the calcium sulfate contained in the superphosphate will react with the dicalcium phosphate, resulting in the formation of the almost insoluble tricalcium phosphate as well as of ammonium sulfate, as follows:

$$\underset{\substack{\textit{dicalcium}\\ \textit{phosphate}}}{2CaHPO_4} + \underset{\substack{\textit{calcium}\\ \textit{sulfate}}}{CaSO_4} + \underset{\textit{ammonia}}{2NH_3} = \underset{\substack{\textit{tricalcium}\\ \textit{phosphate}}}{Ca_3(PO_4)_2} + \underset{\substack{\textit{ammonium}\\ \textit{sulfate}}}{(NH_4)_2SO_4}$$

Naturally, this reaction is only partial, depending upon the amount of surplus ammonia present, but it results in lowering the proportion of phosphorus, which is immediately available, while increasing the content of available nitrogen. In consequence, the various ammoniated superphosphates offered in the trade differ somewhat in composition resulting from different methods employed in their manufacture. In general, they contain 3 to 4 per cent nitrogen and 15 to 18 per cent phosphorus (as P_2O_5). The now cheaply available anhydrous ammonia has made these rather useful products possible.

"Ammo-phos" and "Leunaphos"

"Ammo-phos" tends to increase soil acidity, and its repeated use may cause a sulfur deficiency. For this reason it is advisable to apply powdered limestone together with "Ammo-phos," or to add powdered limestone as filler (see page 332) to mixed fertilizers which contain "Ammo-phos." To prevent sulfur deficiency and at the same time increase the nitrogen content of the material, ammonium sulfate may be added to it, a procedure which has been followed, for instance, in the production of the fertilizer sold in Europe under the name "Leunaphos."

Nitrophoska

Based on ammonium nitrate and ammonium diphosphate are the fertilizers called *nitrophoska,* which are sold in Europe with several different content ratios. They also contain potassium chloride, and they occupy a somewhat intermediate position between the mechanically mixed fertilizers and the chemical compounds. They are produced by first melting the ammonium nitrate and then stirring the other salts into it. The whole mixture then is allowed to set, after which it is ground. The result is that rather uniform aggregates are formed, and the various ingredients are tied to each other much more intimately than mere mixing could achieve.

Dicalcium Nitrophosphate

Dicalcium nitrophosphate, which so far seems to be produced only in Holland, is being experimented with in the United States, where it probably will be manufactured also. It appears to be rather promising. It is produced by treating raw phosphate rock with a mixture of nitric and phosphoric acid.

29. LIQUID FERTILIZERS

It is evident that fertilizer mixtures can be produced just as well in liquid form by merely dissolving the required salts in water. A number of liquid fertilizers are on the market, and the best of them, which are very complete in composition, are closely identical with the nutrient solutions used in hydroponics (see page 169). Vitamins, especially vitamin B_1, are sometimes added also to such liquid fertilizers.

Liquid Fertilizer for the Home Gardener and the Farmer

For the home gardener, who requires only very small amounts of fertilizer to keep his potted house plants in good health, liquid fertilizers are highly recommended. They are eminently safe to use, if properly diluted—usually at the rate of 1 teaspoonful/gal of water—and the harmful overfeeding of potted plants, which is a common error and which can easily happen with solid fertilizers, is much less of a danger.

For the farmer or commercial gardener, suitable mixtures of dry but completely soluble fertilizers are now available and, by dissolving these in the proper proportion in water, he can prepare his own liquid fertilizer. The price of such special fertilizers is still comparatively high, but effects are almost immediate. Leaching losses are negligible because one would never apply large amounts anyhow, and with certain high-value cash crops, where early maturity is important, the additional expense is well justified.

Starter Solutions for the Truck Gardener

The truck gardener, who makes most of his profit with his earliest crops, will find liquid fertilizers useful when he employs them as starter solutions in the planting of tomatoes, celery, pepper, sweet potatoes, lima beans, snap beans, sweet corn, etc. Results obtained leave no doubt that such crops, when watered in with starter solution instead of only with water, ripened as much as a week earlier and gave larger yields besides.

A starter solution, especially when used in setting out young vegetable seedlings, should always be very dilute. Solutions of 6 to 8 lb/100 gal of water, or 1 tablespoonful/gal of whatever composite fertilizer is chosen, have generally been found to be most satisfactory. This is applied at the rate of ¼ to ½ pint to the roots of each plant before covering them with soil. The soil should not be pressed down tightly. Best results are obtained with a starter solution when no dry fertilizer has been incorporated in the soil previous to planting, and when feeding is rather by means of repeated side dressing.

Transplanting Solution

Of similar advantage is the use of liquid fertilizer as starter or transplanting solution in the transplanting of ornamental woody plants (trees or shrubs) with a poor root system. It will often make the difference between a 100 per cent and an only partial recovery of transplanted trees and shrubs. Transplanting solutions are applied either directly to the roots, before the latter are covered, or are placed in a deep furrow, after which 2 to 3 in. of soil are filled in, before the plants are set out. Proportionately larger amounts will be required than those recommended for vegetable seedlings.

Liquid Fertilizer in Irrigation Water

The application of liquid fertilizers, by adding them to irrigation water, is becoming fairly widespread in the coastal districts of California, Oregon, and Washington. Especially the use of anhydrous ammonia (NH_3), which is the cheapest of all sources of nitrogen, appears to be extremely promising; more so, since free ammonia is very readily and quickly adsorbed by the soil, and its uniform distribution presents no technical difficulties.

Drilling in of Liquid Fertilizers

The recently much advocated procedure of drilling an aqueous solution of ammonia or urea as well as phosphoric acid into the soil—either before planting or as a side dressing during the growing season—must also be considered as highly promising. Especially under conditions where water for field irrigation is not readily available, or on steep slopes where ground irrigation is not feasible, the drilling in of these special types of liquid fertilizers has been found to be distinctly superior in effect and efficiency to an application of equal amounts of dry fertilizer.

In parts of California and Arizona this fertilizing procedure has progressed beyond the experimental stage, and, because of excellent results obtained at comparatively low cost, this practice is likely to spread rapidly in the future.

Fertilizer Sprays

Fertilizer sprays containing zinc, copper, and manganese, or either one of these three alone, which are applied to the foliage, are employed particularly in citrus groves to correct deficiencies. They are most serviceable under alkaline soil conditions, where application to the soil is likely to be ineffective. Borax sprays have been found highly effective, for instance, on grapes as well as on rutabagas under conditions where a high soil calcium content prevented satisfactory results from borax applications to the soil.

Complete fertilizer sprays, containing nitrogen as well as phosphorus and potassium, have lately been investigated and show definite promise for certain specific purposes.[1] Street trees, for instance, which are surrounded by asphalt so that root feeding is difficult or impossible, may be helped very appreciably with a fertilizer spray applied 6 times at 2-week intervals from the end of May to early August. The ratio used in the experiments was 23–21–17, and this fertilizer was dissolved at the rate of 1 lb/30 gal of water. One tablespoonful of a synthetic detergent ("Dreft") was added to the solution to increase spreading capacity. Best results were obtained with morning or evening application, but even noon spraying in full sun produced no injury. Such fertilizer sprays may be combined with certain pesticides such as ferbam, DDT or parathion or with the fungicide sulfur. Fertilizer sprays will be found useful also in helping weak plants to become established, in maintaining vigorous growth of garden vegetables during dry periods, or in bringing house plants suffering from the dry air of overheated rooms back to health and vigor, but they can never actually take the place of root feeding and must be considered merely as supplemental. In the greenhouse culture of tropical epiphytes, such as orchids, ferns, bromeliads, aroids, and gesneriads, regular spraying with highly diluted liquid fertilizers will always produce superior results.

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[1] Pirone, P. P., "Trees Need Attention Too," The Garden, New York Botanical Garden, p. 12, 1950.

30. THE RESIDUAL EFFECT OF FERTILIZERS ON SOIL REACTION

QUICK CONVERSION THROUGH CHEMICAL REACTION

As may be seen from Table 31.2, Chapter 31, the aqueous solutions of the various substances and compounds employed as fertilizers or in fertilizer mixtures may have either a neutral, an acid, or an alkaline reaction. (Compare the values given under pH, column 4.) The rather rapid change of some of these substances, on entering the soil, into other substances with a different pH value has been explained previously. As examples may be mentioned the conversion of the highly acid monocalcium phosphate into the neutral diphosphate and of the highly alkaline calcium carbonate into the mildly acid bicarbonate. This type of conversion, resulting from chemical reactions, is quite common when fertilizer materials are added to the soil.

GRADUAL CHANGE THROUGH BIOLOGICAL PROCESSES

Other fertilizer materials are subject to more gradual changes in reaction which are caused largely by physiological processes, depending upon the metabolism of plants and microorganisms. These processes are slow to manifest themselves, and the resulting change in pH value may extend over months or even over several years.

For this reason the various fertilizer materials are generally divided into three groups—the physiologically neutral, the physiologically acid or acid forming, and the physiologically basic. Since this classification is frequently misunderstood or is not understood at all, its meaning will be further explained with a few examples.

Physiologically Acid Fertilizers

When, in order to supplement the nitrogen content of a soil, ammonium sulfate [$(NH_4)_2SO_4$] is applied, the NH_4^+ ion will be used by the plants and the microorganisms much more quickly than the SO_4^{--} ion, which will largely remain in the soil. In consequence, the soil will be acidified. Ammonium sulfate, therefore, is a physiologically acid fertilizer.

Physiologically Basic Fertilizers

When Chile saltpeter [sodium nitrate ($NaNO_3$)] is employed as a source of nitrogen, the nitrate anion will be taken up by the plants in larger amounts, and the sodium cation will be left over in surplus, causing alkalinization of the soil. Chile saltpeter, therefore, is a physiologically basic fertilizer.

FACTORS INFLUENCING THE RESIDUAL EFFECT

The reasons for the preference of plants for either the cation or the anion fraction of a compound are not easy to determine, but it appears that the pH of the soil exerts a certain influence, and different types of plants likewise show differences in their preference. Investigations have revealed that the concentration of the solution also may often have a decisive influence on the preferential uptake of ions.[1]

It has long been known that potassium chloride and sodium chloride have no influence on soil pH, presumably because plants absorb both ions of these compounds equally. Careful experiments have demonstrated, however, that this holds true only at low concentrations, and that the chloride anion is absorbed by plants much more freely than the respective cation (potassium or sodium) when the concentration exceeds 2,000 lb/acre of potassium chloride. Only the formation of bicarbonates then prevents perceptible alkalinization.

Potassium sulfate, on the other hand, is definitely acid forming, and it is mainly this difference in the behavior of the two salts which makes it advisable to apply both together, in mixture, when large quantities of potassium must be incorporated to correct a serious deficiency.

Historical Data

As long as only organic fertilizers were employed, nobody paid any attention to their physiological reaction, because with them this is insignificant. But with the advent of artificial fertilizers and with their ever-increasing use, the situation became rather critical, since many cultivated soils were made too acid for the well-being of the crop plants as well as of the microorganisms.

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[1] Menachem-Starkmann, T., Plant and Soil, I, pp. 82–93, 1948.

Many scientific investigators, such, for instance, as A. L. Mehring,[2] occupied themselves with this problem, and it was pointed out that, especially during the years 1900 to 1933, the use of certain commercial fertilizers produced a harmful acidity in many American soils.

POTENTIAL ACIDITY EQUIVALENT OF CALCIUM CARBONATE

Since that time the picture has changed greatly, and the commercial fertilizers offered today either are nonacid forming, or the potential acidity equivalent of calcium carbonate per ton of fertilizer is stated on the package. This information permits the user to compensate the physiological acidity of the fertilizer through the addition of appropriate amounts of powdered limestone.

Methods Used to Determine Acid-Forming Qualities of Fertilizers

To make it possible to supply this information, reliable laboratory methods had to be developed which permit determination of the acid-forming or nonacid-forming quality of a simple or mixed fertilizer, and to standardize these methods for general use. On the American continent this determination is carried out according to the methods of analysis of the Association of Official Agricultural Chemists.

These methods determine the amount of calcium carbonate which (1) is required to compensate the acidity produced by 100 lb of a physiologically acid fertilizer, or (2) is equivalent to the degree of alkalinity produced by a physiologically alkaline fertilizer.

These methods may be applied to organic as well as inorganic fertilizer materials. Tables 31.2 and 31.3, in Chapter 31, state these calcium carbonate equivalents for most of the important fertilizers. The farmer or gardener who buys his fertilizers from a reliable dealer need, in general, not be concerned about this matter, since all fertilizer producers now carry out the required determinations and take these physiological reactions into full consideration.

MECHANICALLY MIXED FERTILIZERS

Basic Principles of Mixing Fertilizers

The most commonly known and most widely used types of artificial fertilizers are the so-called complete fertilizers, which are mechanically

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[2] Mehring, A. L. and Peterson, A. J., Jour. Assoc. Off. Agr. Univ. 17, p. 95, 1934.

prepared mixtures of different carefully chosen compounds, supplying the most generally needed nutrients, viz., nitrogen, phosphorus, potassium, calcium, sulfur, and magnesium. The three last-named elements are contained mainly in the superphosphate which usually is employed as the source of phosphorus. As nitrogen source are used either ammonium sulfate, ammonium nitrate, sodium nitrate, or urea, or quite frequently, several of these together. Potassium chloride or sulfate or both supply the potassium. As mentioned previously, the various compounds which include more than one important nutrient substance, such as ammonium phosphate, potassium nitrate, and potassium phosphate, are used also in high-grade fertilizer mixtures.

Fertilizer Analysis

In order to use a mixed fertilizer intelligently, it is necessary first of all to make sure of its composition and of the respective amounts of the various nutrients it supplies. This is possible by means of the analysis which, in most countries, the law requires to be stated on the package. To render the analyses understandable, a few explanations are necessary.

According to international agreement, the content of nitrogen, phosphorus, and potassium is always stated in this order: nitrogen first, phosphorus second, and potassium third. Nitrogen is given as N, phosphorus as the anhydride of phosphoric acid (P_2O_5), and potassium as the oxide (K_2O).

In every instance only those amounts are included in the analysis which are presumed to be available to the plants. Of nitrogen, the total is included which will either be available immediately or will become so gradually through biological processes; of phosphorus, the amount which is water or citric acid soluble; and of potassium, usually only the water-soluble part.

These amounts are stated in the analysis as percentages, and the contents of a fertilizer are given, for instance, as: 4 per cent nitrogen (as N), 8 per cent phosphorus (as P_2O_5), and 4 per cent potassium (as K_2O). By general agreement this is simplified to the formula 4–8–4, which means that 100 lb of the fertilizer contain 4 lb of nitrogen, 8 lb of phosphorus (P_2O_5), and 4 lb of potassium oxide.

The amateur is usually puzzled as to what makes up the rest of the 100 lb, since 4, 8, and 4 together amount only to 16. This obscurity actually is quite unfortunate. What must be borne in mind is that these amounts of nitrogen, phosphorus, and potassium are contained in compounds and, if, for instance, nitrogen, is supplied in the form of ammonium sulfate (20 per cent nitrogen), phosphorus as superphosphate (20 per cent P_2O_5), and potassium as potassium chloride (50 per cent K), the following calculation may be made:

100 lb of ammonium sulfate contain 20 lb of nitrogen. Therefore, 4 lb of nitrogen are contained in 20 lb of ammonium sulfate.
100 lb of superphosphate contain 20 lb P_2O_5. Therefore, 8 lb P_2O_5 are contained in 40 lb of superphosphate.
100 lb of potassium chloride contain 50 lb of potassium. Therefore, 4 lb of potassium are contained in 8 lb of potassium chloride.

Together, this amounts to 68 lb. The rest of the 100 lb (32 lb) consists of an inert filler material—in North America usually diatomaceous earth, fuller's earth, clay, carbon flue dust, talc, or vermiculite—which serves mainly to make up the weight, so as to provide a fertilizer with the above ratio 4–8–4 in 100 lb.

Fertilizer Fillers

Fertilizer fillers—or fertilizer conditioners, because the proper type of filler does serve as a conditioner by preventing caking of the finished product after it has been bagged—are very little understood by the average fertilizer user yet are of considerable importance. It is evident that to purchase large quantities of a low-ratio fertilizer is uneconomical, because of the filler material it contains. In the above case, for instance, one third of the total weight is filler, while the cost of transportation, a considerable part of the total expense, depends upon the total weight. In addition, a large part of the cost of a mixed fertilizer accrues from mixing, handling, and packing expenses, which are always the same no matter what the fertilizer contains. In consequence, the production cost as well as the sales price of a ton of high-ratio fertilizer is only very slightly higher than that of a ton of fertilizer with a low ratio. Since much less of the former need be applied to obtain the same effect, an all-around saving results which, where large amounts are concerned, may be very considerable.

Usefulness of Certain Fillers. Unfortunately, no fertilizer formula states what kind of filler is used, though this information would be valuable. Diatomaceous earth, which is completely inert and without any fertilizer value, is employed most commonly but by no means exclusively. When powdered limestone, and especially dolomitic limestone, is used instead, this would be worth knowing, since this material is neither inert nor worthless. Not only does it supply readily available calcium and magnesium; it also will compensate the possible physiological acidity of some of the chemical compounds included in the mixture.

Organic Materials as Fillers. Certain organic materials, such as tankage or even peat, which sometimes are used instead of inert fillers, are not worthless either. In fact, their addition to the soil is very beneficial. In addition, such organic materials tend to keep the chemical compounds dry and to prevent them from caking. For this reason they are frequently termed *fertilizer driers.* The fertilizer formula, as such, however, gives no information as to whether such materials have been included or not.

It is equally unfortunate that the average fertilizer formula does not indicate what carrier substances are used to supply the respective amounts of nitrogen, phosphorus, and potassium. One has no way of knowing, for instance, whether nitrogen is present in the form of ammonia or nitrate or urea; whether phosphorus is supplied as superphosphate, phosphate rock, or "Ammo-phos," etc. Yet such information would certainly be very helpful in using these fertilizer mixtures to best advantage. This fact is ever more generally realized, and, with at least some of the commercial fertilizers, statements of composition are now provided. In some states they are even prescribed by law. These are called "open formula guarantees." It is very much to be hoped that this practice will become general.

The Advantages of Machine-Mixed Fertilizer

What has been said so far may suggest to the farmer that the best procedure for him to follow would be to obtain separately the various compounds he wishes to use and to mix them himself in the proportion best suited to his particular requirements. This is a tempting idea and actually is quite frequently advocated. It has a number of very serious disadvantages, however, as follows:

(1) The average farmer or gardener is rarely able to judge which fertilizer materials may be mixed safely and without running the risk of incurring very considerable losses in fertilizer value. (See Figure 32.1, Chapter 32.)

(2) The effect of a mixed fertilizer depends very largely upon an equal distribution which, again, depends upon the evenness and thoroughness of the mixture. Mixing by hand, no matter how carefully it is done, can never produce as uniform a mixture as can mixing by a machine which has been specially constructed for the purpose.

(3) A mixed fertilizer, in order to spread easily, must be well and evenly granulated. This can easily be achieved by machine, where grain size can be controlled very accurately, whereas it is next to impossible by hand.

For these reasons a ready-mixed fertilizer, purchased from a reliable dealer, can generally be expected to give better results than one which has been mixed by hand.

Most Favorable Ratio of a Mixed Fertilizer

The question now foremost in the reader's mind undoubtedly is: What is the ratio between nitrogen, phosphorus, and potassium which is most likely to give satisfactory results when applied to the soil in a fertilizer mixture? Not only is there no agreement on the answer to this question, but, instead, vast confusion exists. This is illustrated by the fact that, in the United States alone, fertilizer mixtures with over 600 different ratios were at one time offered commercially. No doubt exists that this represents an utterly needless complication, and that only a small fraction of these actually are required.

This matter, however, cannot be discussed without first considering the nitrogen-phosphorus-potassium ratio in the soil, and what it means as far as plant growth is concerned, so that a correlation becomes possible. Since this would lead too far afield from the topic covered in this part of the book, which deals merely with fertilizers as such, the subject is left to Part VI.

31. IMPORTANT DATA ON FERTILIZER MATERIALS

In order to provide a clearer perspective of the properties of the various organic and inorganic fertilizer materials, four tables have been prepared for convenient comparison. The information given in these tables permits not only the evaluation of a fertilizer but also the computation of the formula of a mixed fertilizer when its ratio and components are known. Table 31.1 gives conversion factors. The following explanations will facilitate use of the remaining tables.

Table 31.2 lists the chemically pure inorganic salts which are contained in either simple or combined fertilizers.

Column 1. The designation of the salts is given according to the rules for naming inorganic compounds of the international union for chemistry (1938).

Column 2. The chemical formula and, in particular, the amount of water of crystallization applies to the most commonly employed chemically pure salts.

Column 4. The pH value was determined potentiometrically in an aqueous solution of the chemically pure substance at a temperature of 25°C (77°F).

Column 5. The solubility is expressed in grams of the salts which are soluble in 100 ml water at 20°C (68°F), according to the "International Critical Tables." To convert the solubility into pounds in United States gallons, the figure given in the table should be multiplied with 0.08345. Salts, which decompose in water, are marked "d"; sl. s. means "slowly soluble"; v. s. means "very soluble."

Column 6. The percentage content is given in elemental form as nitrogen, phosphorus, potassium, etc.

Table 31.1 will serve to convert these values into the equivalents in oxides, acids, or salts.

Tables 31.3 and 31.4 list, respectively, the *commercial* inorganic and organic fertilizer materials. The numbers in front of the names in Table

TABLE 31.1. CONVERSION TABLE

Element	Desired equivalent	Factor with which the figure found in the table must be multiplied
N (nitrogen)	$(NH_4)_2SO_4$ (ammonium sulfate)	4.7166
"	NH_4Cl (ammonium chloride)	3.8191
"	HNO_3 (nitric acid)	4.4986
"	NH_3 (ammonia)	1.2159
P (phosphorus)	P_2O_5 (anhydrous phosphoric acid)	2.2912
"	H_3PO_4 (phosphoric acid)	3.0801
K (potassium)	K_2SO_4 (potassium sulfate)	2.2285
"	KCl (potassium chloride)	1.9069
"	K_2O (potassium oxide)	1.2046
Ca (calcium)	CaO (calcium oxide)	1.3992
"	$CaCO_3$ (calcium carbonate)	2.4973
Mg (magnesium)	MgO (magnesium oxide)	1.6579
Na (sodium)	Na_2O (sodium oxide)	1.3479
Cl (chlorine)	HCl (hydrochloric acid)	1.0284
S (sulfur)	SO_3 (sulfur trioxide, sulfite)	2.4971
"	SO_4 (sulfate)	2.9962
"	H_2SO_4 (sulfuric acid)	3.0586
C (carbon)	CO_2 (carbon dioxide)	3.6644

31.3 refer to the corresponding alternate names listed at the bottom of that table. The following explanations apply to both lists:

Column 2. Commercial products of this type vary considerably in composition; the values given, therefore, are averages.

Column 3. For the meaning of physiological soil reaction, see page 328.

Column 4. The figures given represent the amounts of calcium carbonate (powdered limestone), in pounds, which are required to compensate the residual acidity of 100 lb of a physiologically acid fertilizer, or which are equivalent to the residual alkalinity of 100 lb of a physiologically basic fertilizer. For instance, when 100 lb of ammonium sulfate/acre are to be applied, one will find in the table that 110 lb/acre of powdered limestone are required to compensate the residual acidity. Residual alkalinity is usually compensated by means of elemental sulfur at the rate of 32 lb of flowers of sulfur/each 100 lb of calcium carbonate equivalent.

TABLE 31.2. PURE INORGANIC SALTS CONTAINED IN FERTILIZERS

1	2	3	4	5	6									
					Composition, %									
Material	Formula	Mol weight	pH	Solubility	N	P	K	Ca	Mg	Na	Cl	S	C	B
Ammonium sulfate	$(NH_4)_2SO_4$	132.14	4.8	75.7	21.2	—	—	—	—	—	—	24.23		
" chloride	NH_4Cl	53.50	5.2	37.2	26.18	—	—	—	—	—	66.28			
" nitrate	NH_4NO_3	80.05	4.0	194.0	35.0									
" phosphate, mono	$NH_4H_2PO_4$	115.07	4.1	37.4	12.17	29.93								
" " , di	$(NH_4)_2HPO_4$	132.11	7.9	59.4	21.20	23.46								
" carbonate	$(NH_4)_2CO_3 \cdot H_2O$	114.11	8.3	—	12.27	—	—	—	—	—	—	—	10.51	
Ammonia anhydrous	NH_3	17.03	—	—	82.22									
" water (28%)	$NH_4OH \cdot nH_2O$	—	—	—	23.0									
Potassium sulfate	K_2SO_4	174.25	7.0	11.1	—	—	44.87	—	—	—	—	18.39		
" chloride	KCl	74.55	7.0	34.3	—	—	52.44	—	—	—	47.56			
" nitrate	KNO_3	101.1	7.0	31.1	13.68	—	38.67							
" phosphate, mono	KH_2PO_4	136.13	4.5	30.0	—	9.97	22.79							
" " , di	K_2HPO_4	174.22	8.8	v s.	—	17.80	44.88							
" " , tri	K_3PO_4	212.31	—	sl s.	—	14.61	55.24							
" metaphosphate	KPO_3	118.12	7.0	sl s	—	33.09	26.23							
" carbonate	$K_2CO_3 \cdot 2H_2O$	174.23	11.6	139.0	—	—	45.8	—	—	—	—	—	6.09	
Calcium hydroxide	$Ca(OH)_2$	74.10	12.5	0.16	—	—	—	54.07						
" sulfate	$CaSO_4 \cdot 2H_2O$	172.17	7.0	0.26	—	—	—	23.28	—	—	—	18.62		
" chloride	$CaCl_2 \cdot 2H_2O$	147.03	7.0	v s	—	—	—	47.26	—	—	48.23			
" nitrate	$Ca(NO_3)_2$	164.10	6.5	v s	17.06	—	—	24.42						
" phosphate, mono	$Ca(H_2PO_4)_2 \cdot H_2O$	251.17	2.5	d	—	24.6	—	15.89						
" " , di	$CaHPO_4 \cdot 2H_2O$	127.14	6.5	0.02	—	18.02	—	23.28						
" " , tri	$Ca_3(PO_4)_2$	310.28	6.7	0.0025	—	19.99	—	38.75						
" carbonate	$CaCO_3$	100.08	9.5	0.0015	—	—	—	40.05	—	—	—	—	12.0	
" cyanamide	$CaNCN$	80.10	12.2	d	34.98	—	—	50.04						
Magnesium hydroxide	$Mg(OH)_2$	58.34	11.0	0.001	—	—	—	—	60.32					
" sulfate	$MgSO_4 \cdot 7H_2O$	246.49	6.8	71.0	—	—	—	—	9.81	—	—	12.95		
" chloride	$MgCl_2 \cdot 6H_2O$	203.33	7.0	167.0	—	—	—	—	11.96	—	34.88			
" nitrate	$Mg(NO_3)_2 \cdot 6H_2O$	256.43	7.0	42.33	10.09	—	—	—	9.48					
" carbonate	$MgCO_3$	84.33	10.3	0.011	—	—	—	—	25.0	—	—	—	2.47	
Sodium sulfate	$Na_2SO_4 \cdot 10H_2O$	322.21	7.0	42.8	—	—	—	—	—	14.27	—	9.95		
" chloride	$NaCl$	58.45	7.0	37.0	—	—	—	—	—	39.5	60.5			
" nitrate	$NaNO_3$	85.01	7.0	87.7	16.46	—	—	—	—	27.01				
" phosphate, mono	$NoH_2PO_4 \cdot H_2O$	138.05	4.2	110.0	—	22.47	—	—	—	16.66				
" " , di	$Na_2HPO_4 \cdot 7H_2O$	268.13	9.3	—	—	13.02	—	—	—	17.16				
" " , tri	$Na_3PO_4 \cdot 12H_2O$	380.20	12.1	25.8	—	8.16	—	—	—	18.15				
Sodium carbonate	$Na_2CO_3 \cdot 10H_2O$	286.17	11.8	59.8	—	—	—	—	—	16.07	—	—	4.19	
" tetraborate (borax)	$Na_2B_4O_7 \cdot 10H_2O$	381.44	9.5	4.5	—	—	—	—	—	12.05	—	—	—	11.36

TABLE 31.3. COMMERCIAL INORGANIC FERTILIZERS

	1	2						3	4	
		Average Composition, %, total							Residual effect upon soil reaction lb $CaCO_3$	
	Material	N	P_2O_5	K_2O	CaO	MgO	SO_3	Physiological soil reaction	Required to neutralize the physiological acidity from 100 lb fertilizer	Equivalent of physiological alkalinity from 100 lb fertilizer
1	Ammonia, anhydrous	82	—	—	—	—	—	Acidic	148	
2	Ammonia solution	22	—	—	—	—	—	"	40	
3	Ammonium chloride	24	—	—	—	—	—	"	128	
4	" sulfate	20	—	—	—	—	59	"	110	
5	" nitrate	33	—	—	—	—	—	"	60	
6	" sulfate-nitrate	26	—	—	—	—	28	"	85	
7	" phosphate, mono	11	48	—	1.5	0.5	6	"	55	
8	" " , di	21	53	—	—	—	—	"	74	
9	" " , "-sulfate	20	20	—	—	—	36	"	93	
10	" " , mono- "	16	20	—	0.5	—	38	"	86	
11	Basic slag, Bessemer	—	18	—	47	4	0.5	Basic	—	?
12	" " , open hearth	—	12	—	45	5	0.5	"	—	?
13	Calcium cyanamide	21	—	—	54	—	1	"	—	63
14	" nitrate	15	—	—	28	—	—	"	—	21
15	" " -urea	34	—	—	13	—	—	Acidic	28	
16	" ammonium nitrate	20	—	—	15	2	—	Neutral		
17	" phosphate, meta	—	64	—	23	—	—	"		
18	" " , di	—	25	—	30	—	—	Basic	—	?
19	" carbonate	—	—	—	50	—	—	"	?	?
20	" sulfate	—	—	—	32	—	46.5	Acidic		
21	Carnallite, crude	—	—	10	—	8	—	Neutral		
22	Kainite, crude	—	—	18	—	5	10	"		
23	"Nitrophoska"	12	12	22	9	1.5	3	Acidic	?	
24	Phosphate rock	—	35	—	48	2	7	Basic	—	?
25	Potassium carbonate	—	—	65	—	—	0.5	"	—	?
26	" chloride	—	—	55	2	2	0.5	Neutral		
27	" sulfate	—	—	50	2	1	45	"		
28	" nitrate	13	—	44	0.5	0.5	—	Basic	—	23
29	" phosphate, mono	—	52	27.5	—	—	—	Neutral		

30	” metaphosphate	—	55	38	0.5	—	—	”		
31	” *sodium nitrate*	*15*	—	*15*	—	—	—	Basic	—	26
32	” magnesium sulfate	—	—	25	2	12	45	Neutral		
33	” ammonium chloride	13	—	22	—	—	—	Acidic	70	
34	” ” *phosphate*	*5.5*	*54*	*18*	—	—	—	”	?	
35	Superphosphate (20%)	—	20	—	25	0 5	30	Neutral		
36	” ” (40%)	—	40	—	20	0.5	2.5	”		
37	” ” ammoniated *(20%)*	*4*	*15*	—	*25*	*0.5*	*30*	Acidic	5	
38	” ” ” (40%)	6	45	—	18	0.5	2.5	”	12	
39	” ” -urea	7	15	—	15	0.3	25	”	13	
40	*Sodium nitrate*	*16*	—	—	—	—	—	*Basic*	—	28
41	Ashes, bone	—	35	—	46	1	0 5	”	—	?
42	” , cottonseed hull	—	5.5	27	9.5	5	2.5	”	—	55
43	” , sunflower stalk	—	*2.5*	*36*	*18*	?	—	”	—	?
44	” , tobacco	—	3	23	22	6	5.5	”	—	?
45	” , wood	—	2	5	32	3.5	1	”	—	?

SYNONYMOUS NAMES

2 Ammonia liquor, B-liquor, ammonium hydroxide
3 "*Salammoniac*", *muriate of ammonia*
6 "Leuna salpeter"
9 "Leunaphos"
10 "*Ammo-phos*" *A*
11 "Thomas meal"
13 "Nitrolime", Kalkstickstoff

15 "Calurea"
16 "Cal-Nitro", nitro-chalk
18 "Fertiphos"
19 Limestone (with variable content of $MgCO_3$)
23 *Also other trade names*
25 Potash, technical grade

26 Muriate of potassium or potash
31 Nitrate of soda-potash
32 "Kali-magnesia"
33 "Potazote"
39 "Phosphazote"
40 Chile saltpeter

TABLE 31.4. COMMERCIAL ORGANIC FERTILIZERS

1	2						3	4	
	Average Composition, %, total							Residual effect upon soil reaction lb $CaCO_3$	
Material	N	P_2O_5	K_2O	CaO	MgO	SO_3	Physiological soil reaction	Required to neutralize the physiological acidity from 100 lb fertilizer	Equivalent of physiological alkalinity from 100 lb fertilizer
Manures, fresh									
Cattle	0.5	0.2	0.6	0.8	0.2	0.1	Basic	—	?
Horse	0.7	0.2	0.7	0.6	0.4	0.2	"	—	?
Goat	0.4	0.3	0.9	0.6	?	?	"	—	?
Chicken	1.5	1.0	0.4	1.2	0.3	0.6	"	—	?
Sheep	1.4	0.5	1.2	1.7	0.7	0.5	"	—	?
Pig	0.5	0.3	0.4	?	?	?	"	—	?
Manures, dried									
Cattle	2.0	1.5	2	4	1	0.5	"	—	?
Horse	2	1.5	1.5	1.5	1	0.5	"	?	?
Goat	1.5	1.5	3	2	?	?	"	—	22
Chicken	5	3	1.5	4	1	2	Acidic	?	
Sheep	2	1.5	3	5	2	1.5	Basic	—	?
Compost, fresh	0.5	0.4	0.5	?	?	?	"	—	?
Sewage sludge, dried	2	2	—	2.5	0.5	0.5	Acidic	?	
" " , activated, dried	6	3	0.5	2.5	1.5	1	"	10	
Tankage, garbage, dried	2.5	3	1	4.5	0.5	1	Basic	—	10
" , animal, "	7	10	0.5	15.5	0.5	1	"	—	15
Guano, bat	8.5	5	1.5	7.5	0.5	2	"	?	
" , Peruvian	13	12	2.5	11	1	3.5	"	13	
Meals, animal									
Bone, raw	4	22	—	31.5	1	0.5	"	—	30
Blood, dried	13	1.5	1	0.5	?	?	Acidic	25	
Fish, dried	9.5	7	?	8.5	0.5	0.5	"	8	
Horn	14	1	?	2.5	0.1	2	"	?	
Residues, vegetable									
Castor pomace	5.5	1.5	1.5	0.5	0.5	—	"	8	
Cocoa shells	4	2	2.5	1.5	0.5	—	Neutral		
Cottonseed meal	7	2.5	1.5	0.5	0.5	0.5	Acidic	15	
Linseed meal	5.5	2	1.5	0.5	1	1	?	?	?
Rapeseed meal	5.5	2.5	1.5	1	0.5	0.5	?	?	?
Soybean meal	7	1.5	2.5	0.5	0.5	0.5	Acidic	?	
Tobacco stems	2	0.5	6	5	0.5	1	Basic	—	25
Wool waste	3.5	0.5	2	0.5	—	?	?	?	?
Seaweed, air dry	1.5	0.5	2	3	1	3.5	?	?	?
Urea	46.6	—	—	—	—	—	Acidic	75	

32. THE COMPATIBILITY OF FERTILIZER MATERIALS

The fact that fertilizer materials cannot be mixed at random is frequently not realized yet must not be overlooked. The reason is that certain substances react upon each other, which results in chemical conversions causing either loss in nutrient value or deterioration of physical properties. Lumpiness or an increased attraction for moisture, having an adverse influence on the facility with which the fertilizer can be spread,

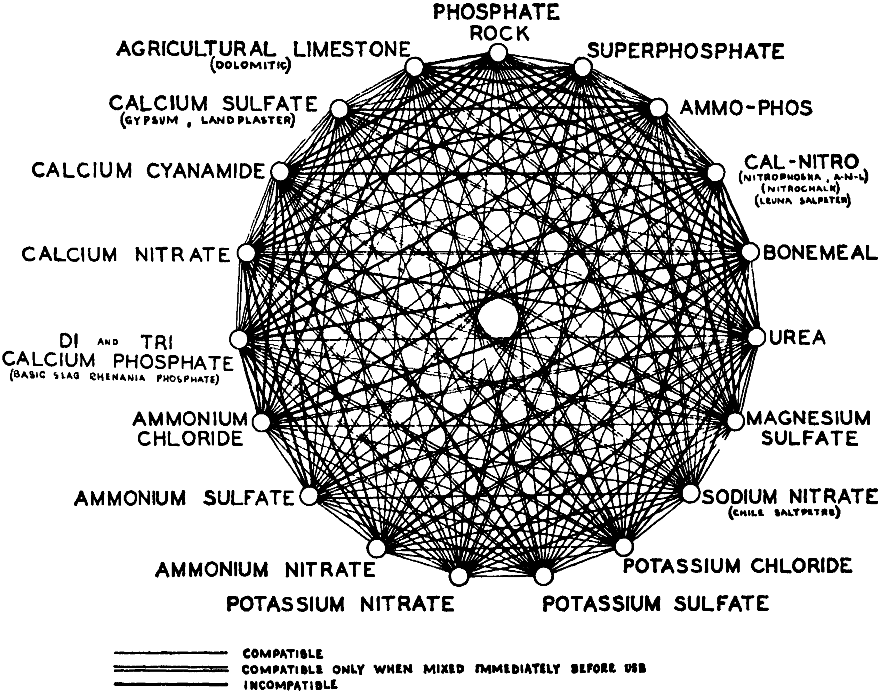

Figure 32.1

may result from chemical conversions. Commercial producers of mixed fertilizers consider the compatibility of the ingredients, and the farmer who wishes to mix his own fertilizers must likewise do so.

The fertilizer star, Figure 32.1,[1] permits the determination, at a glance, as to which fertilizer substances can be mixed safely. The designation "compatible" means that the mixture will keep permanently, provided it is stored dry and is not exposed to rain or sun. "Compatible only when mixed immediately before use" means that the ingredients must not be mixed more than 1 or 2 weeks before the fertilizer is applied to the soil. The designation "incompatible" means that these substances must not only never be mixed with each other but should not even be applied to the soil at the same time.

The fertilizer star, as such, is self-explanatory, but a few examples may be cited to show the type of valuable information which it supplies. Urea, for instance, can be mixed with potassium sulfate but is incompatible with potassium chloride (muriate of potash). A mixture including both urea and potassium chloride shows a strong tendency to form hard lumps.

When superphosphate and basic slag are mixed with each other, phosphorus availability is sharply lowered. When ammonium sulfate is added to calcium cyanamide, free ammonia develops which escapes into the air. This means that a mixture of these two substances results in a loss of nitrogen.

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[1] Adapted from Ullmann's Encyclopedie der technischen Chemie, 1930 (revised and enlarged 1951).

PART VI

The Laws of Soil Fertility

INTRODUCTION

The laws here discussed are the laws of nature, not laws made by man to govern nature which is impossible. Actually man himself is a part of nature, and, therefore, is also subject to nature's laws.

Through long-term close observation and through the recording and comparison of the circumstances which influence a natural process, it is possible to establish and to predict what effect follows what cause. This, then, is a natural law which, from a sufficiently large number of carefully controlled, checked, and rechecked observations, can be formulated and can be expressed in a mathematical equation. Such an equation then permits the computation, in advance, of what is going to happen when certain natural forces are set in motion or are caused to act upon each other.

Since the amounts of nutrients which plants can obtain from the soil as well as the effect of these nutrients, in proper proportion to each other, on the growth of plants must likewise be subject to natural laws, it is tempting to try formulating these laws. If this can be done, it will then be possible to compute mathematically what the nutrient requirements of plants are and what actually represents a favorable nutrient balance. This attempt has actually been made, and the results, though they cannot be considered final or absolute, are so enlightening and the logic of the procedure followed is so intriguing that they deserve to be treated in detail.

The manner in which natural laws in general are formulated and employed may be explained first.

Laws of Nature Governing a Falling Body

The scientific observation of a falling object which has been dropped from a height will be taken as an example. The observer will want to know two things: First, how long does it take the falling object to hit bottom, and, second, what is its speed at every moment throughout the fall. A sufficient number of observations and measurements will enable him to formulate two natural laws which causally are intimately connected, viz., "the general law," which governs the process as a whole, and "the momentary law," which is responsible for what happens at every individual smallest moment throughout the process. From the mathematical formulas expressing these laws, various facts can be computed, depending on which are known and which are unknown in each given case.

Application of Natural Laws

For instance, when the weight and the surface area of the falling object are known, the air resistance which it will meet and which will retard its fall can be computed from previously developed formulas. With these facts known and with the time measured which it took the object to hit bottom, the above-mentioned formulas will make it possible to determine the height from which the object has fallen. In the same manner and with the aid of similar formulas, the exact moment at which the object will hit bottom or the spot where it is going to land can be foretold. Thus it can be seen that such formulations of natural laws are of immense value and can serve as invaluable tools in all scientific endeavor.

Evidently, the more sharply such a law expresses the actual natural process, the more accurate will be the values that can be computed by it. The aim, as stated, for instance, by the famous physicist and chemist W. Nernst, must be "to fashion the mathematical formula which expresses a natural law into as close an image of the natural process as a photograph is of the object which it pictures."

Short-Interval Measurements Required for Sharp Definition

For this reason, the scientist, when expressing a natural process mathematically, usually splits the process into the smallest possible fractions or intervals, designating the latter by mathematical symbols. The expediency of this procedure may be explained by referring once more to the simile of the photograph. The closer, for example, the individual pictures of a movie film follow each other, the easier it becomes for the spectator to observe accurately whatever movement is depicted. In the same manner will a mathematical formula expressing a natural law approach reality the more closely, the shorter are the intervals covered by the measurements on which its formulation was based. This shows that the precision and perfection of the measuring methods are the main limiting factors, and that man's capacity to penetrate the workings of nature is limited by the extent of his knowledge and the precision of his tools. In consequence, formulations of natural laws are not absolute and are open to revision as science advances. On the other hand, they are universal and are applicable everywhere throughout the world.

Infinitesimal Calculus

The very short intervals mentioned above can be dealt with only by means of a special branch of mathematics, termed *infinitesimal calculus,* which permits carrying out computations with values too small for human senses to perceive. This branch of mathematics, which includes differential and integral calculus and which was first established by J. Newton (1642–1713) and G. W. Leibnitz (1646–1716), is very highly developed now and has aided immeasurably in advancing science in general to its present high level.

A special difficulty in mathematical formulation is presented by a large number of natural processes which, instead of following a certain course and then coming to a final stop, diminish so gradually, with ever-increasing slowness, that the actual end can be neither perceived nor measured. As far as human perception can establish, they approach an end rather than reach it, and one has to deal with limit values instead of measuring an end condition. The following condensed description of the behavior of radioactive substances, which were chosen as an example, will facilitate understanding of the laws of soil fertility, to be discussed later.

Disintegration of a Radioactive Substance

Radioactive substances give off rays and, by doing so, gradually diminish in mass. The latter fact leaves no doubt that this type of radiation actually is a disintegration. All radioactive substances have one peculiarity in common: The more atoms of the substance are present, the more of these atoms in proportion are subject to disintegration; the fewer atoms are present, the smaller becomes the proportion which decays. In other words, the speed of disintegration of radium, or of any other radioactive substance, is proportional to the amount present.

An Asymptotic Process. The consequence is that, as disintegration proceeds, it becomes slower and ever slower and that—though the substance never disappears completely—its amount gradually becomes so infinitesimally small that it can no longer be perceived or measured. The scientist expresses this by saying that the process approaches zero asymptotically.[1] The total life period of a radioactive substance, therefore, cannot be established, since it is infinite. On the other hand, such substances gradually diminish to such an extent that the infinitesimally small amount which finally may still be present is, for all practical purposes, as good as nonexistent.

The Half Period of Life. Since any attempt to fix a line of practical nonexistence must meet with failure, while for mathematical computations some definite value must be established, one resorts to the expedient of defining, by means of experiments and observations, not the total but the "half period of life." This term applies to the time it takes for half of a given amount of a radioactive substance to disintegrate, which can be computed once the ratio according to which disintegration gradually diminishes has been established. It may seem strange that the half period of life of the same radioactive substance is always the same, no matter how much or how little of it is present, but this results from the fact that the speed of disintegration diminishes in perfect proportion to the amount present. Because of the faster disintegration of larger amounts, it is possible also to compute the amount present from the strength of the radiation.

In this manner it was established, for instance, that the half period of life of radium is approximately 1,800 years, whereas that of the gaseous radon, one of the decay products of radium, is about 5 days. One must always bear in mind, however, that twice the half period of 1,800 years (3,600 years) does not represent the total period of life of radium. Because of the gradually diminishing speed of decay, proportionate to the amount present, the half period of life of the remaining portion is still 1,800 years and the half period of what is left after that is again 1,800 years. So on and on to infinity. The terms *asymptotic process* and *half period of life* will appear again in the following description of the laws of soil fertility which is the reason why they were explained here.

The authors freely admit that the laws of soil fertility are in need of further perfection, but the logical approach they offer to a problem which, so far, has been solved only empirically by trial and error is of undeniable value. The practical application of the formulas (though their correctness is much under dispute) produces results which come surprisingly close to the figures that are generally accepted.

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[1] An asymptote is a line which gradually approaches closer and closer to a curve without ever actually becoming a tangent to it.

33. THE FUNDAMENTAL CONCEPTS ON WHICH THE LAWS OF SOIL FERTILITY ARE BASED

Growth Factors

The natural processes which govern the growth of plants are—as is the case with all the phenomena of life—still not completely explored in all their deepest ramifications. There are still numerous gaps in our basic knowledge, and the objection, therefore, is frequently raised that it is futile to attempt a formulation of the laws of soil fertility with such imperfect tools. This may be answered by stating that somebody has to make a beginning if our aim is to find a logical approach to this extremely complex problem. It certainly is possible to establish principles even with imperfect tools, and the explanation of these principles, as they emerge from the work of Mitscherlich, Spillman, Wilcox, Bray, and others, is the main aim of the following discussion. Once the logic of the reasoning is accepted, the next step is the perfection of the formulas which have been developed.

The scientist who sets out to study the course of a natural process, in order to establish the natural law which governs it, must first identify the various forces and circumstances which influence it. When this is done for the growth of plants, it is immediately apparent that the general circumstances influencing plant life, such as climatic conditions and soil conditions, are much too vague in concept to be delimited and defined. For application, these complex concepts must be broken down into definable factors which can be circumscribed as far as their character is concerned, and which vary only in amount or quantity.

The effect of each individual factor on the course of the natural process—in this case on the growth of plants—must then be established so that it can be expressed by a mathematical symbol for use in an equation.

The combined effects of all the factors together will permit the computation of the course of the process so that its end result can be predicted. This, at least, is the theory of the procedure which is rather overwhelming in its logic. How reliable the prediction will be depends on the precision of the measurements and the correctness of the figures used in the computation.

The decisive factors which govern plant life are generally termed "growth factors," and Table 33.1 enumerates some of the most important ones.

TABLE 33.1. GROWTH FACTORS INFLUENCING PLANT DEVELOPMENT

Main group	Growth factors included in the group
Climatic conditions	Insolation or amount of available light Temperature of the air Amount and distribution of precipitation Oxygen and carbon dioxide content of the air and of the soil atmosphere
Physical condition of the soil	Stone content of the soil Size of the soil particles Depth of the top soil Depth of soil cultivation Height of the water table Water-holding capacity of the soil Soil temperature Colloidal condition of the soil governing its acid-base-exchange capacity Buffering action of the soil Soil pH value
Sowing	Condition of the seeds Type of plants sown Time of sowing Density of sowing
Plant nutrients	The amounts of the various nutrients present, which must be considered individually as well as in their proportion to each other

Table 33.1 makes no pretense to be complete; it is intended to serve only as an indication of what is meant by the term *growth factor.* The following discussion will treat only the plant nutrients, and of these only the three most important ones, viz., nitrogen, phosphorus, and potassium, which have been studied in greater detail than all the other growth factors. The laws of soil fertility, as they emerge from this study, are equally applicable to all other growth factors.

The logical procedure, when investigating the influence of one particular nutrient—such as nitrogen—on the yield, is to apply increasing amounts of this nutrient to separate series of plants, so that the results can be compared. Naturally, such an experiment can produce interpretable results only when the other nutrients—in this case phosphorus and potassium—remain unchanged at a favorable level for all the plants throughout the experiment. The other growth factors, such as light, water, and carbon dioxide content of the air, must be the same for all the plants under observation. In other words, observation of the variable factor which is being investigated must not be allowed to become clouded by the influence of other factors. If this were permitted, it would be impossible to identify the cause of an effect.

The Proportionality Constant

To render the conclusions drawn from such experiments generally applicable, one other difficulty must be overcome, viz., that all soils already contain certain varying amounts of nutrients, with the result that the addition of equal amounts of a nutrient to different soils will produce different crop yields.

Reasoning in trying to overcome this impasse led to the conclusion that a nutrient, or any other growth factor, should be considered entirely divorced from the medium—the soil or air—in which it acts merely as a power, a certain quantity of which must be capable of producing a certain measurable quantity effect. In other words, what is needed for mathematical computation is the decisive constant figure which expresses the quantity effect of each growth factor, entirely independent of the individual requirements of plants, the varying climatic conditions during their long vegetative period, and the composition of the soil.

This is a large order which, at first glance, seems quite impossible to fill. Actually, this constant figure, termed the *proportionality constant,* has been computed. (See Appendix II for the equations used to do so.) Undoubtedly this figure is not perfect, and the statement is frequently made that the statistics upon which the computations were based were not entirely reliable. They probably were not. Even Mitscherlich himself has[1] revised the original figure for the value of the proportionality constant which was 0.301 to 0.2, which shows clearly that it was not, and probably is not now, 100 per cent correct. But the very audacity of the attempt deserves credit, and the results obtained, even with the imperfect figure, are amazingly sensible, as will be outlined farther.

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[1] Mitscherlich, E. A., and Atanasiu, N. *Z. Acker- u. Pflanzenbau,* **94,** 253 (1952).

Two additional concepts which must be included in a formulation of the laws of soil fertility are the maximal crop yield and the maximal soil fertility.

Maximal Crop Yield

Maximal crop yield refers to the highest possible yield which a given type of plant can produce on a given unit area of land under the most favorable soil conditions and at the maximal density of stand. It is evident that a certain limited area cannot produce an unlimited quantity of vegetable substance, and the amount which actually can be produced will, even under absolutely ideal conditions, gradually approach a limit representing the maximum. Because the principles involved apply to all plants in general, Willcox has proposed the term *maximum quantity of life* instead of the original *maximal yield* (*Hoechstertrag*) used by Mitscherlich. Since it is more cumbersome, and since only crop plants are being considered here, Willcox's term has not been employed in this text.

Theoretically, the maximal yield is 100 per cent, and this figure can readily be inserted in a mathematical equation for the computation of other values. (See Appendix II.) The figures quoted in Chapter 34, explaining the law of diminishing yield increment as well as the highest yields practically reachable, were obtained by means of such computations. Since plants vary greatly in water content, the statistics used in developing and formulating the fundamental theories were based on the dry, not the fresh, weight of the plant material. With crop plants, only that part of the plant which represents the actual crop was employed, i.e., with grain crops, the grains, and with root crops, the roots or tubers.

The unit area of land used in such computations is, in English-speaking countries, the acre and in continental Europe, as well as in many other parts of the world, the hectare (2.471 acre).

Maximal Soil Fertility

Though the present discussion treats only nutrient factors and, of these, only the three most important ones, this is sufficient to explain the principle. Evidently, when even only one of these three plant nutrients is entirely absent, plant growth will be impossible, and when any one of them is deficient (present in insufficient amounts), maximal yield cannot be expected.

The problem, therefore, is to find a common denominator which can be employed in an equation, so that it becomes possible to compute mathematically what proportional available amounts of the various plant nutrients a soil must contain in order to produce maximal yield, no matter what kind of crop plant is being raised.

This seems to be as impossible as the development of the proportionality constant, because it is generally recognized that different types of plants, when considered individually, differ in the amounts of the various nutrients which they absorb from the soil (as can be proved by ash analysis). From this fact it is commonly concluded that plants differ also in their requirements, some, for instance, needing more nitrogen than others, etc. This premise, however, may be faulty; the reasoning here applied assumes that it is faulty, if, instead of individuals, one considers the total of all the plants of a certain type which can succeed on a delimited area such as 1 acre. What confuses the issue is the nutrient balance, especially the proper balance between nitrogen, phosphorus, and potassium. (See Chapter 39.) In an unbalanced soil the emphasis remains on different nutrients with different plants because of inherent variations in tolerance to unbalance. (See page 395.) Maximal yield, though, cannot be obtained under such conditions.

Reaction of Plants to an Ideally Fertile Soil

For the sake of mathematical computation an ideally fertile soil—or, as Willcox has termed it, a *perfertile* soil—which contains all the required nutrients in perfect balance and in optimum amounts, is the basic requirement. Under such conditions the reasoning assumes that, though individual plants of different types or species differ widely in their content of nitrogen, phosphorus, potassium, etc., when all the plants fully occupying an acre are taken together, their total content in any of these elements is always the same, regardless of the type of plant being investigated. The presupposition explaining this conclusion is that the same unit area cannot support the same number of plants of a large and vigorous species as of a small weak-growing species.

This reasoning is much disputed and its validity is frequently questioned, but it must be admitted that its logic is fascinating. Its acceptance does supply the required common denominator, which may be restated as follows: All plants, no matter of what type, withdraw equal amounts of nutrients from the same unit area of ideally fertile soil to produce their maximal yield, no matter how large or small this maximal yield may be. This means that, though each type of plant has its own characteristic maximal yield (the highest it can produce), on an ideally fertile soil each and all will produce their maximal yield, because under such ideal conditions all plants will be subject to the same nutritional pressure. The amount of the maximal yield will then be governed solely by their inherent capability as determined by their hereditary make-up. On this premise it will be possible also to compute the ideal nutrient balance which will be applicable equally to all kinds of plants. No matter whether one is willing to accept this reasoning or not, it is very much worth while to follow it to its ultimate consequences, as will be done here, because the results to which it leads are worthy of serious consideration.

34. THE DEVELOPMENT AND FORMULATION OF THE LAWS OF SOIL FERTILITY

Introductory Remarks

The information most wanted by the student of soil will be: "What proportional increase in yield can be expected to result from the application of increased amounts of fertilizer?" or, in somewhat more technical language, "What quantitative relation exists between the crop yield and the influence of the various growth factors, in particular, of the nutrients or fertilizer?" This is a vital question, since it touches the pocketbook of the practical grower. Fertilizers cost money, and, if the increase in yield is negligible, the money spent on fertilizer is wasted. A very large increase, on the other hand, especially when many follow the same procedure, may result in unsalable crop surpluses or in a sharp drop in prices, so that once again the money is wasted. In the latter case a reduction in area would be the logical answer. Raising the same amount of yield on a much smaller area would save so much on labor that the cost of additional fertilizer as well as a minor price drop could easily be absorbed.

Every grower will have to make his own decision on these points. Obviously, he would be greatly benefited if he were able to calculate in advance what effects on the yield could be expected from the various measures serving to ameliorate the soil.

Historical Data

The first to carry out a systematic investigation of this problem was Boussingault who, in his paper "*Recherches chimiques sur la végétation entreprises dans le but d'examiner si les plantes prennent de l'azote à* *l'atmosphère" (1838)*,[1] quoted numerous pot experiments by means of which he tried to establish the influence of varying amounts of nutrients on the growth of plants. Though his researches failed to show clear quantitative correlations between the amount of yield and the amount of nutrients present, they served to point the way to those who followed. Real progress in this field had to await the work of Liebig, some 15 to 20 years later.

Liebig's Law of the Minimum

One of the most widely known of the many accomplishments of Liebig is his formulation of the law of the minimum, which proclaims that crop yield is limited by the amount of that nutrient which is present in smallest amounts. This implies that when, for instance, phosphorus and potassium are present in correspondingly larger amounts than nitrogen, the yield will depend only on the available nitrogen, and the addition of further amounts of phosphorus and potassium does not increase it. This very plausible statement was generally accepted for a long time but has since been shown to be only partly correct. Actually, the yield does increase, even when only more phosphorus and potassium or more of either one of the two is added. Naturally, the lack of nitrogen will gradually become more pronounced and will most definitely prevent optimal results, but only when the unbalance is carried too far will growth disturbances and, eventually, nitrogen-deficiency symptoms appear. Up to that point there will be a certain increase in yield.

Law of Diminishing Yield Increment

Liebig believed, furthermore, that the addition of nutrients to the soil produced a proportional increase in yield. Mitscherlich (mainly 1909–1930) and Willcox proved that when nutrients are added to a soil in such a manner that the amounts present are first doubled, then tripled, then quadrupled, etc., the yield does not increase in the same proportion. Instead, the increment (the increase in yield) gradually becomes smaller and smaller, the closer one approaches the maximal yield. The natural law which governs this phenomenon, and which was deduced from Mitscherlich's findings, is termed the *law of diminishing yield increment*.[2]

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[1] "Chemical Researches on Plants Undertaken with the Purpose of Finding Out Whether Plants Absorb Atmospheric Nitrogen."

[2] The term *law of diminishing returns*, which is employed in the United States, is misleading, because the return itself—the crop yield—does not diminish but actually continues to increase. Only the proportionate increase—the increment—in

Its main significance is that it permits the determination of how close to the maximum it is economically feasible to raise the yield through further additions of fertilizer.

The Standardized Culture Pot

For the careful control of general conditions during nutrient studies, Mitscherlich introduced an exactly dimensioned culture pot [20 cm (7.8 in.) in diameter and depth] which now is widely employed for these and similar purposes. Table 34.1, showing the effect of the addition of nitrogen (in carefully graduated equal steps) on the yield increase of oats, is based on such culture-pot experiments. Only available amounts were considered, and the amount of 0.35 g of nitrogen per pot corresponds to approximately 100 lb/acre. When the other growth factors are kept constant, the results given in the table are obtained (according to Willcox).

Table 34.1. Diminishing Yield Increment with Increasing Amounts of Nitrogen

Amount of nitrogen (N) in the soil, g	Proportional increase in N	Dry weight of yield of oats, g	Increment in yield for each step
0	—	0	0
0.35	Single	80.0	80.0
0.70	Double	120 0	40.0
1.05	Triple	140.0	20 0
1.40	Quadruple	150 0	10 0
1.75	Quintuple	155.0	5.0

This shows that when no nitrogen is present the yield is zero. The addition of 0.35 g of nitrogen produces a yield of 80 g. When this amount of nitrogen is doubled, the yield is not doubled; instead of 160 g only 120 g, or only half as much more as the previous yield, is obtained. The triple amount of nitrogen produces 140 g (not 240 g), again only half as much more as the increase produced by the double amount. The increment in yield continues to diminish in the same manner with each successive step.

Exactly the same experiment has been carried out with oats for phosphorus (computed as P) with absolutely identical results, showing that

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yield diminishes. For this reason, the expression chosen by Gericke, S [*Z. Pflanzenernähr. Düng., Bodenk.*, 39, p. 245 (1947)], "Gesetz des abnehmenden Erntezuwachses," has been rendered as "law of diminishing yield increment" and is used in this text as being more descriptive.

the increments in yield in response to successive equal increases in nutrient represent a "decreasing geometric series." The assumption which suggests itself is that this applies equally to all nutrients as well as to any other growth factor.

A still clearer picture of the relation of nutrient increase to crop yield is obtained when the latter is expressed graphically by means of a curve. (See Figure 34.1.) The horizontal axis shows the increase in nutrients in equal amounts, and the corresponding crop yield is entered on the vertical axis in percentages of maximal yield.

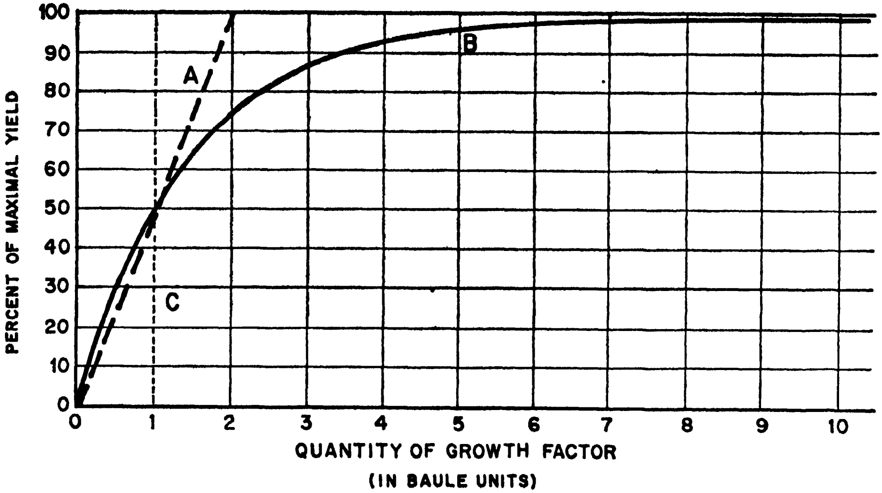

Figure 34.1

If the crop yield would increase in proportion to the increase in nutrient—according to the concept of Liebig—the rise of the yield would be represented by the straight line *A*. Instead of doing so, the yield increase follows line *B*. The latter at first rises rather steeply, showing that, in the beginning, the increase in yield is considerable. As more nutrients are added, the curve gradually commences to flatten out and approaches the horizontal axis asymptotically. (See page 347.) This means that it never actually becomes truly horizontal and that an absolute 100 per cent of maximal yield can never be reached. Therefore, on an ideally fertile soil, plant growth, in theory at least, never reaches but only approaches an end condition. That trees do not grow into the sky results from the fact that growth gradually diminishes to such an extent that it becomes infinitesimal or, for all practical purposes, zero. Aging, resulting from other causes, sets a limit to their life anyhow.

Baule Units

The similarity between these processes and the previously described disintegration of radium is readily apparent. Here too, it is not possible to express mathematically the absolute value of the end condition, and the logical conclusion is to resort to the same expedient of establishing the value of half of the process in order to obtain a usable figure. In this case it is the "half quantity of life" (or half of maximal yield) rather than the half period of life, as with radium.

This suggestion was first made by the German mathematician Baule in his paper "*Zu Mitscherlichs Gesetz der Biologischen Beziehungen*" ("To Mitscherlich's law of biological relationships") where he proposes to employ the amount of any growth factor which produces 50 per cent of maximal yield as a basic unit in mathematical computation. This unit, generally designated as "a Baule unit" or simply "1 Baule," has been used in the preparation of the curve shown in Figure 34.1.

Amounts Which Represent 1 Baule Unit. The amounts of the various nutrients, in particular of nitrogen, phosphorus, and potassium, which are capable of producing 50 per cent of maximal yield and, therefore, represent 1 Baule unit have been established empirically by means of large numbers of experiments with living plants. The figures thus obtained have been checked and rechecked by numerous experimenters in the field, as well as in pot culture with many different types of plants, and they have always proved surprisingly reliable. This, perhaps, is Mitscherlich's greatest accomplishment, to which he has devoted a large part of a long lifetime. To be sure, there is still disagreement, and many soil scientists are reluctant to accept these figures. Nor is any claim made here that they might not be open to further amendment. But nobody can deny that they represent milestones on the road to deeper insight and progress. Their greatest value probably lies in the proportion between the three most important nutrient elements which they reveal. Practical application shows that these cannot be very far from the truth.

The figures as they stand at present are as follows:

1 Baule per acre:

Nitrogen (N)—225 lb
Phosphorus (P)—19.6 lb (as P_2O_5—45 lb)
Potassium (K)—68 lb (as K_2O—82 lb)

Employment of these figures—even if one considers them as tentative—makes it possible to calculate, by means of the law of diminishing yield increment, how far it is economically worth while to go with the addition of fertilizers. (See Appendix II.) Table 34.2 shows the results. The percentages of maximal yield, given in the last column, apply to each of the three nutrient elements individually, but always with the proviso that the other two, as well as all other growth factors, are at 10 Baule units, representing optimum conditions. For a computation of the yield which can be expected when none of the three principal elements, nitrogen, phosphorus, and potassium, is present in optimal amounts, see Chapter 38.

Table 34.2. Baule Units of Nitrogen, Phosphorus, and Potassium and the Percentage of Maximal Yield They Produce

Baule units	Corresponding lb/acre			Crop yield in percentages of maximal yield
	N	P	K	
0.5	110.2	9.8	34	29.20
1.0	220.5	19.6	68	50.0
2.0	441.0	39.2	136	75.0
3.0	661.5	58.8	204	87.5
4.0	882.0	78.4	272	93.75
5.0	1,102.5	98.0	340	96.83
6.0	1,323.0	117.6	408	98.44
7.0	1,543.5	137.2	476	99.22
8.0	1,764.0	156.8	524	99.61
9.0	1,984.5	176.4	612	99.80
10.0	2,205.0	196.0	680	99.90

4 to 5 Baule Units the Economical Limit

The pronounced flattening of the curve (Figure 34.1) above 7 Baule units suggested already that it can hardly be worth while to raise the crop yield beyond this point through further addition of fertilizer. Table 34.2 shows that the economical limit must be set even lower. Beyond 4 Baules, or at most 5 Baules, the increase in yield becomes so small that the application of still larger amounts of fertilizer would clearly be a waste of money.

35. INTERPRETATION OF THE AMOUNTS DETERMINED BY SOIL ANALYSIS

Assuming that, in view of the eminently sensible results obtained with them, the figures used in Chapter 34 are at least tentatively accepted, their application may be carried somewhat farther.

The value of soil analysis hinges on the dependability of its interpretation in terms of plant response. As long as there is no correlation between the amounts determined and the amounts required to produce a definable quantity effect, soil analysis can have no value whatsoever.

The difficulty of establishing such a generally acceptable correlation is of long standing and actually has prevented soil analysis from being fully recognized as the valuable aid it can be. One possible means is to use Baule units for comparison, according to the values given in Table 34.2, provided that soil analysis is carried out in such a manner that *only* those amounts of each nutrient substance are extracted and determined which are at the immediate disposal of the plants. This touches upon another serious difficulty in the interpretation of soil analysis, which consists in lack of general agreement on extraction procedures. It is evident that comparable results cannot be obtained if different methods of extraction are employed by the various experimenters.

Evaluation of Soil Analysis for Potassium

Agreement is most nearly general on the extraction of potassium which may, therefore, be used here as an example for possible rationalization of soil-analysis interpretation.

Readings of 4 to 5 Baules—or 300 lb/acre of potassium—are interpreted as very good. That 6 Baules—400 lb/acre of potassium—are interpreted as high derives from the fact (see Chapter 20) that available amounts of potassium are always backed up by large, temporarily unavailable reserves. The latter become available automatically when part of the available potassium is used by the plants. In consequence, it is even less economical with potassium than with most other plant nutrients to raise the soil content above 5 Baules, especially since, with increasing amounts, an ever-larger percentage of the added potassium becomes unavailable as soon as it enters the soil. The average natural soil fit for cultivation rarely contains more than 4 Baules of available potassium, and usually much less.

TABLE 35.1. AMOUNTS OF AVAILABLE SOIL POTASSIUM, AS DETERMINED THROUGH SOIL ANALYSIS, CORRELATED WITH BAULE UNITS AND WITH NUTRIENT VALUES

Available amounts obtained by analysis in lb/acre	Equivalent in K_2O	Interpretations	Baule units	
			As computed	Rounded off
50	62.2	Deficient	0.76	0.8
75	90.3	Very low	1.10	1.0
100	120.4	Low	1.47	1.5
150	180.6	Medium	2.20	2.0
200	240.6	Good	2.94	3.0
300	361.2	Very good	4.4	4 to 5
400	481.6	High	5.9	6.0

Repeated application of large amounts of potassium fertilizer to cultivated soils without control through analysis occasionally raises the content of available potassium to well over 1,000 lb/acre. Such an excess has no toxic effect but is likely to cause considerable trouble through interference with other nutrients. In addition, it represents wasted money, and the lost nutritional balance is very difficult to restore, showing clearly that soil analysis, properly interpreted, can be very useful indeed.

Phosphorus

Phosphorus acts in the soil in a manner very similar to potassium, but its extraction from different types of soil so as to produce comparable results is more difficult, and agreement on extraction procedure is far from general. It has even been suggested that different methods of extraction be used for different soil types. This would make a standardization of evaluation entirely impossible. To avoid controversy, phosphorus, therefore, will not be discussed here, though if comparable amounts of the immediately available phosphorus are extracted, their correlation with Baule units is as workable as with potassium.

Nitrogen

Very different is the situation with nitrogen, which becomes available gradually through bacterial activity and throughout the warm season. (See Chapter 18.) Its two available forms, ammonium and nitrate, are not present in full amount at the beginning of the season, as is the case with potassium and phosphorus. Neither do they behave alike. Nitrate, being 100 per cent soluble, is subject to leaching, and, in consequence, the amounts present fluctuate widely. Ammonium, which is adsorbed by the soil colloids, is much more steady. For an evaluation, both must be extracted and their potential source, which is soil organic matter, must be examined also. In other words, the capacity of a soil to produce nitrogen rather than its momentary content of available nitrogen must be determined. This is not easy, because a certain amount of nitrogen is always and unavoidably lost, not only through leaching of the nitrate but also through volatilization of ammonia. How much this is depends on numerous and complex circumstances. No more than an approximation, therefore, is possible, but this is quite sufficient for the reasoning which follows.

Limit to Which Soil Nitrogen Content Can Be Raised. As previously demonstrated, application of the Mitscherlich principles leads to the conclusion that 4 to 5 Baule units represent the approximate limit to which it is economical to raise soil fertility. Even 4 Baules of nitrogen, however, amount to 882 lb/acre. Is it possible to supply such a huge amount of nitrogen and to maintain it throughout the growing season? This much is certain, that no natural or cultivated soil ever contains a sufficiency of suitable organic matter to develop the equivalent of 4 to 5 Baule units of available nitrogen.

Supplying Additional Nitrogen—Maximal Amounts. How far may it be practically possible to go in supplying nitrogen to the soil? The following calculations will provide a tentative answer.

(1) A well-maintained cultivated soil is likely to contain an average of 150 lb/acre of nitrogen (as $NH_4 + NO_3$) or at least sufficient organic matter to develop this amount during the growing season.

(2) Inorganic nitrogen can be added most readily in ammonium form, though a distinct limit exists when ammonium sulfate is used. Field experiments have shown that the maximum amount, still safe under average conditions, is 710 lb/acre of ammonium sulfate, supplying 150 lb/acre of nitrogen. Beyond that, one risks creating toxic conditions through the formation of overlarge amounts of nitrite.

(3) In addition, one may plow under 10 tons of fresh farmyard

manure which—not considering losses—would supply 11 lb of nitrogen ton = 110 lb/acre; as well as 6 tons of a good compost, supplying 15 lb of nitrogen/ton = 90 lb/acre, amounting to 200 lb/acre of organic nitrogen.

The three items together would supply a total of 500 lb/acre of nitrogen, which corresponds to about 2¼ Baule units and which would be capable of producing approximately 80 per cent of maximal yield. (See Table 34.2.) This high yield is an ideal one which is reached only when both phosphorus and potassium as well as all other growth factors are at 10 Baules. The figures serve only for comparison but they bring out that 2¼ to 2½ Baule units of nitrogen represent the approximate upper limit to which soil nitrogen supplies can be pushed.

In fact, a soil to which both items 2 and 3 are added in the proposed quantities is "loaded" and is not safe against nitrite toxicity. The computation has been made in this manner only to show limits. Ammonium sulfate should never be applied in such large amounts together with a large quantity of manure. "Uramite" would be very much safer. It contains 38 per cent nitrogen, of which approximately 80 per cent becomes available gradually during the first 6 months. Therefore, 500 lb "Uramite" would supply about the same amounts of nitrogen as 710 lb of ammonium sulfate. Even with "Uramite," though, 500 lb/acre together with manure and compost may not be entirely safe.

The general conclusion, therefore, remains that 2¼ Baule units represent maximal amounts for soil nitrogen content and, under most circumstances, one will have to be satisfied with less. This means that nitrogen is always a limiting factor which, for this reason alone, has to be watched with particular care.

With these conclusions in mind, a tentative evaluation of soil nitrogen content from analysis may be suggested (Table 35.2).

TABLE 35.2. AMOUNTS OF AVAILABLE SOIL NITROGEN, AS DETERMINED THROUGH ANALYSIS, CORRELATED WITH BAULE UNITS AND WITH NUTRIENT VALUE

Available amounts obtained by analysis in lb/acre N (in NH_4)	Available amounts obtained by analysis in lb/acre N (in NO_3)	Total available N in lb/acre	Interpretation	Baule units
10	5	15	Deficient	0.06
20	10	30	Low	0.1
50	25	75	Medium	0.35
100	50	150	Good	0.7
200	100	300	Very good	1.4
400	200	600	High	2.7

Since nitrate and ammonium, which have to be extracted and determined separately, do not, when considered separately, give a clear idea of the nitrogen resources of the soil, the two have been tabulated together. Again, it depends on extraction methods whether the values here given are applicable or not. These cannot be discussed here and will have to be standardized first. The aim of this table is merely to demonstrate how the Mitscherlich principles can serve in arriving at standardization through the application of logic.

That slightly more than ½ Baule of nitrogen is evaluated as "good" is based on the fact that ammonium and nitrate develop gradually during the season and should not be present in large amounts at any one time.

Soil Ammonium and Nitrate in Relation to Each Other. The relationship between ammonium and nitrate shown in the above tabulation is ideal rather than factual and may need revision. For a true evaluation of a soil, the following facts must be considered.

When 100 lb/acre of nitrogen as nitrate are found in a natural soil to which no nitrate has been added, this actually is a high level, since it is rarely surpassed under natural conditions. At this level the nitrifying bacteria apparently become more or less inactive. Ammonium production likewise seems to be suppressed, as long as nitrate content remains so high, and usually is present only in amounts of 25 to 50 lb/acre. This is one phase of the nitrogen problem which is still in need of further investigation.

Whether a soil which, in analysis, shows this type of relationship between ammonium and nitrate is actually as good as it appears to be depends on its humus content. If an analysis for total humus shows not less than 2 to 5 per cent, this means that sufficient reserves are present from which more ammonium and more nitrate can be produced for some time and that this is a good soil as far as nitrogen is concerned. If there are no such reserves, a soil of this type will produce only a few good crops, after which it will show signs of exhaustion. Nitrogenous organic matter must be added to it as soon as its lack of reserves is revealed through analysis. This interplay between ammonium and nitrate must always be considered in any interpretation of a nitrogen soil analysis.

Capacity of a Soil for Nitrogen Production. The season of the year at which soil nitrogen content is determined makes a big difference also. At the end of winter the nitrate content of any soil is always at its lowest, whereas the peak of the season for nitrate in the Northern Hemisphere is usually early August. The capacity of a soil for the production of nitrate is most readily established when an early spring analysis is compared with a summer analysis. The ammonium content of the average good soil, sufficiently supplied with organic matter, changes very little during the season. A decided drop in ammonium content in fall, in comparison with a spring analysis, is a warning signal. It means that the soil requires the application of manure or other rich organic matter, or that it should be given a rest as pasture for a few years.

36. WATER AS A GROWTH FACTOR

In order to show how promising it is to calculate soil fertility by means of growth factors, two others may be considered from the same viewpoint. The many actions of water make it a particularly interesting factor, its three vitally important functions as far as plants are concerned being the following:

Functions of Water

✓(1) It serves as a true nutrient, since it supplies the hydrogen which is indispensably required in photosynthesis (page 101). As such, it acts very much like any other nutrient compound, such as ammonium carbonate, of which also only the cation fraction is utilized. As is the case with other nutrients, water is used in only comparatively small amounts for its hydrogen fraction, though without it, carbohydrates such as sugar and starch cannot be produced.

✓(2) It serves as the sustaining liquid, the very life blood of plants, filling all cells, keeping them turgid (from *turgidus*—swollen, distended), so that soft green stems can stand upright and young leaves can be spread out flat to the sun. In this function, water remains unchanged as H_2O, and it is the only compound on earth which acts in this manner in a living organism. Evidently, this function is as indispensable as the first, since optimum development of plants cannot be expected when the water supply is insufficient to keep the stems upright and the leaves fully extended.

✓(3) It serves as a carrier. The various nutrient substances can enter the plants and can be utilized by the latter only in their ionic state, which means in aqueous solution. (See ions, page 30.)

In order to establish what relation exists between the amount of water present in the soil and the yield, as well as in how far water follows the law of diminishing yield increment, means must be devised which permit the separation of the influence of the other nutrients which water unavoidably carries. The water-holding capacity of the soil, its field capacity (page 84)—which varies widely with different types of soil—must be taken into account also, since, especially under field conditions, it is the capillary water which is most decisive.

Procedure Followed in Establishing the Influence of Water as Such

The general procedure followed by Wollny, Mitscherlich, Vasiliu, Willcox, and others may be outlined as follows:

Carefully calculated amounts of nutrients were first thoroughly incorporated in the soil in its natural state. Mitscherlich, for instance, added to 10 kg of soil (the amount required to fill one of his standard pots) 4.65 g of epsom salts ($MgSO_4 \cdot 7H_2O$); 1.5 g of sodium chloride ($NaCl$); 37.5 g of calcium nitrate [$Ca(NO_3)_2 \cdot 4H_2O$]; 3.82 g of dibasic potassium phosphate (K_2HPO_4); and 2.75 g of ammonium nitrate (NH_4NO_3). The soil then was dried until it contained only hygroscopic water, and was filled into the pots. Water then was added in percentages of the previously determined field capacity of the soil: 10, 20, 30, up to 100 per cent. An equal number of seeds was placed in each pot, and the respective percentage of field-capacity water was carefully maintained through addition, as required, throughout the growing period. At maturity the plants were dried and weighed. The results showed that with most crops an optimum was reached between 60 and 80 per cent of field capacity which declined rapidly when this level was exceeded.

Influence of Field Capacity

Another set of experiments, designed to study the influence of field capacity and therewith of water, as such, on yield, employed pure sand to which increasing amounts of muck soil were added. (See Table 36.1.) Since pure quartz sand of medium grain size shows next to no capillarity, whereas the water-holding capacity of muck soil is exceptionally high, this procedure created a graduated increase in field capacity and, therewith, in readily available water.

Effect of Water Follows Law of Diminishing Yield Increment

The evidence presented by Table 36.1 of the increase in yield produced by increasing water supply is very clear. At the same time, the last column shows that the effect of water is perfectly comparable to that of other nutrients. In conformity with the law of diminishing yield

TABLE 36.1. INFLUENCE OF FIELD CAPACITY AND THEREWITH OF WATER ON YIELD

Volume proportion of sand to muck soil	Water content at field capacity, cc	Average yield of mustard, g of dry weight	Yield, g, computed with the law of diminishing yield increment	Step-by-step increase in yield, g
1.0 : 0.0	1,000	33.9	34.4	
0.9 : 0.1	1,240	40.4	39.5	5.1
0.8 : 0.2	1,480	43.9	43.8	4.3
0.7 : 0.3	1,720	46.8	47.7	3.3
0.6 : 0.4	1,960	49.6	50.7	3.0
0.5 : 0.5	2,200	58.7	52.9	2.2
0.4 : 0.6	2,440	55.5	55.1	2.2
0.3 : 0.7	2,680	55.3	56.8	1.7
0.2 : 0.8	2,920	54.6	58.3	1.5
0.1 : 0.9	3,160	59.8	59.6	1.3
0.0 : 1.0	3,400	62.9	60.6	1.0

increment, the proportionate increase in yield becomes smaller and smaller with each successive step.

In another series of experiments, fertilizer was given only in liquid form but in the same amounts and proportions as had previously been mixed with the soil. In this case a sandy soil was used, and in one series of pots water was supplied by weight in increasing amounts, some pots receiving 500 cc, others 750, 1,000, 1,500, and 2,000 cc. In a parallel series the soil volume was reduced, corresponding to the amount of water supplied, so that in each case the soil could be kept at full field capacity. In the latter series low amounts of water produced much higher yields than in the first series. (See Table 36.2.)

TABLE 36.2 POT CULTURE OF WHITE MUSTARD IN SANDY SOIL—NUTRIENTS SUPPLIED IN LIQUID FORM

	Pots completely filled with soil water supplied by weight	Volume of soil reduced corresponding to the amount of water supplied, so that soil was at field capacity
Water, cc	Average yield, g, of dry weight	Average yield, g, of dry weight
500	32.2	42.9
750	38.5	46.6
1,000	44.1	46.4
1,500	45.2	42.2
2,000	46.4	48.8

Effect of Water Increases with Increasing Content of Nutrients

Table 36.2 shows that with the water supply at field capacity (last column at the right) the yields were almost the same in all five pot series.

The reason for this undoubtedly was that the nutrients supplied in liquid form remained fully available in the soil as long as water was at field capacity, whereas they were partly adsorbed by the colloids of the soil of the first series which was not at field capacity in water content. This shows plainly that liquid fertilizers are fully effective only when accompanied by irrigation which satisfies field capacity.

At the same time it demonstrates that the effect of water increases greatly with the amounts of nutrients it carries, which means that when water contains all required nutrients, a much smaller amount of such water suffices for a certain yield than when water is poor in nutrient content.

Practical Conclusions

The following practical conclusions may be drawn from the above discussion:

(1) Since water follows the law of diminishing yield increment, the amounts required become proportionately larger and larger, the higher the yield is raised. On the other hand, it is the capillary water alone which actually counts, and the amount of capillary water which a soil can hold depends on the texture, structure, and composition of the soil. Therefore, it is evident that sandy soils, because of their low field capacity, cannot produce yields as high as can soils with a satisfactory content of inorganic or organic colloids (clay or peat). This means that a sandy soil can be rendered much more fertile merely by increasing its water-holding capacity through the incorporation of clay or peat.

(2) For highest yields an ample supply of water to field capacity is just as important as a properly balanced and sufficient amount of other nutrients. Where water cannot be supplied to provide the optimum, the yield will be correspondingly lower in spite of ample nutrition.

(3) The fact that the effectiveness of water increases with its nutrient content means that, under conditions where water is at a premium or where one is dealing with a soil of low field capacity, it is particularly important to supply a well-balanced and ample nutrition. Though highest yields are impossible under such conditions, proper nutrition will make it possible to economize on water and still obtain a satisfactory yield. In other words, well-nourished plants can get along with less water —have a greater resistance to drought—than poorly nourished plants.

37. THE DEPTH OF THE CULTIVATED SOIL AS A GROWTH FACTOR

Characteristics and Origin of Topsoil

Though natural sedimentation may result in placing fertile soil layers at varying depth, the biologically most active and, therefore, also the most fertile part is always near the surface. This is the well-known and much-discussed topsoil. The most important distinguishing features of topsoil are its higher content of humus, its active bacterial life, and its looser structure. Very frequently, such topsoil is not only modified because of better aeration but is actually of different origin than the lower soil, having been deposited over the latter by ice, water, or wind, or having developed from decaying vegetation. The subsoil may consist of clay or sand or glacial gravel as well as of any conceivable mixture of these. Solid rock as a substratum a few feet below the surface, which, of course, occurs also, need not be considered here, since such conditions are of no interest to the cultivator.

Topsoil Depth for Soil Analysis

The average depth of topsoil is generally taken to be 7 in. The reason for this is that plowing usually does not penetrate deeper, and that, in consequence, these 7 in. are the most thoroughly mixed section of the soil, carrying most of whatever manure and fertilizer may have been added. For soil analysis, therefore, this measure of 7 in. still stands. (It is accepted also by the Association of Official Agricultural Chemists.) This, however, must not be taken to mean that the soil below this depth is of no importance and that no attention need be paid to it. It should need no emphasis that the actual depth of the topsoil as well as the over-all depth of what may be termed fertile soil are very important growth factors. Since the roots of most of our cultivated annual plants readily penetrate to a depth of 6 ft, and certain perennial plants, as well as most trees and many shrubs, send their roots down as far as 20 ft and even more, the importance of subsoil should be obvious.

Experimental Proof That Yields Increase with Depth of Topsoil

This fact has been beautifully confirmed by the investigations of Wollny,[1] who used field plots under conditions where the subsoil consisted of glacial gravel. He excavated down to the gravel and then filled in the same kind of gravel in heights varying in regular steps from zero to 20 in. The rest of the excavation he filled with a sandy loam soil, creating in this manner a topsoil depth varying on the various plots from 4 to 20 in. On these plots he raised over a number of years some 29 different types of plants, carefully recording the results obtained. His findings were later evaluated by Mitscherlich,[2] who showed that the yields increased with increasing topsoil depth and that the increase followed very neatly the law of diminishing yield increment, becoming gradually smaller. According to Mitscherlich, however, there still is a distinctly worth-while increase at a topsoil soil depth of 80 in.

Reasons for Yield Increase with Deep Topsoil

At first glance one might be inclined to conclude that the increase in yield resulted merely from the fact that the plants had a larger volume of soil at their disposal from which to draw nourishment. As was shown rather clearly in Chapter 36, however, this would be a misconception. There is no doubt that the decisive factor is the loose structure of the soil and, in particular, the depth to which this favorable structure extends. In the first place, this creates a sure and steady supply of water which is much more safely held at some distance below the surface. Besides, it must be assumed that the easier it is for plant roots to penetrate the soil, the less energy must be expended in this effort. Energy being a very precious commodity, whatever is saved of it in one place is available for use elsewhere. A stronger development of the above-surface parts of the plant is therewith made possible.

Horticultural Procedure for Loosening Soil Deeply

Horticulturists have long been aware of the fact that top-quality vegetables or flowers can be raised only on a deeply worked soil, and, especially when raising vegetables for exhibition purposes, they will go

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[1] Wollny, E., *Forsch. Agriculturphysik,* **20, 306** (1897/98).

[2] Mitscherlich, E. A., "Bodenkunde," 6th Ed., p. 225, Paul Parey, Berlin 1950.

to the trouble of turning their soil by hand as much as three or even four full spade cuts deep. The details of this procedure, such as whether the first and the second cut can be exchanged with each other or whether each cut has to be turned separately, depend, of course, upon the condition of the lower-level soil, or on whatever previous treatment it has received, and will not be outlined here. It will be sufficient to point out that the well-known benefits which accrue result mainly from the improvement of the physical condition of the soil.

Plowing and Subsoil Plowing

Neither the farmer nor the truck gardener can afford this type of deep soil preparation, nor is this necessary for the average satisfactory crop. The main purpose of the above paragraph is to emphasize the great advantage offered by a deep topsoil where it can be obtained, and to point out how very worth while it is to pay attention to the depth of the topsoil when new land is purchased. Beyond that, every farmer knows that his plow must not go beyond topsoil depth, since to bring subsoil to the surface will most assuredly lower his yields. To loosen the soil more deeply, however—not by plowing but by means of special tools which do not bring the subsoil to the surface—will usually be distinctly advantageous. Especially in heavy clayey soils, which are inclined to develop at plow depth a so-called "plow sole"—a tightly compressed layer which plant roots cannot penetrate—it is necessary to loosen up the subsoil with a subsoil plow at least every 3 or 4 years. A similar loosening of less heavy subsoil every 5 or 6 years will always be of great assistance to any crop. Experiments with the placing of fertilizer at the time of subsoil plowing to a depth of 14 to 24 in. appear to be promising when the subsoil is definitely low on plant nutrient content. Ground limestone may be applied at the same time when the pH value of the subsoil is below 6.[3] The importance of breaking up a so-called hardpan, which is likely to develop under very sandy soils, and the best means of doing so, have been discussed in Chapter 23.

Effect of Stone Content of Topsoil

Studies have also been made by Wollny and Mitscherlich concerning the influence on fertility exerted by the stone content of topsoil. These investigations confirmed scientifically that yields decline in proportion to the increasing content of stones. Since the inert stones replace their volume of soil, this might be expected. What makes these studies signifi-

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[3] *Purdue Univ. Agr. Expt. Sta. Ext. Leaflet No. A Y, 67a* (1954).

cant is that they revealed the depressing effect of the stone content to be much smaller than it is generally believed to be. Wollny demonstrated that stone content becomes really detrimental only when it amounts to 40 per cent or more of the total soil volume. Quite naturally, different types of plants varied somewhat in their response. Potatoes and peas, for instance, gave appreciably lower yields only at a stone content of over 50 per cent, and corn and beets showed a very noticeable drop in yield at approximately 35 per cent. Response to stone content will vary, furthermore, with the nature of the soil surrounding the stones, as well as from year to year with the amount of precipitation. The latter variation results from the fact that a high stone content increases the drainage and lowers the field capacity. The farmer usually removes the larger stones which plowing brings to the surface, and the smaller ones generally are rightly ignored.

Stone Mulching

The use of stones as a surface covering for the purpose of storing heat and of conserving moisture—practiced especially in vineyards but also in forestry as well as in certain garden cultures—has nothing to do with the effect of stones incorporated in the soil.

38. THE SOIL-FERTILITY INDEX

The mathematical approach in the study of soil fertility can be carried much farther and some of the conclusions thus reached will be given. The great variables which most particularly interfere with a purely mathematical approach will be treated in Part VII (page 384).

Still to be considered is: What proportion of maximal yield can be expected when none of the three main plant nutrient elements—nitrogen, phosphorus, and potassium—are present in optimum amounts, corresponding to 10 Baules. The following computation can be made from the previously developed figures: It may be assumed, for instance, that a soil contains 1 Baule of nitrogen (computed for the whole growing season), corresponding to 50 per cent of maximal yield; 2 Baules of phosphorus, corresponding to 75 per cent of maximal yield; and 3 Baules of potassium, corresponding to 87.5 per cent of maximal yield. At first glance this might lead one to conclude that, under such conditions, nitrogen will act as the limiting factor (according to Liebig's theory) and that a yield of 50 per cent maximum can be expected. Actually, this is not the case, and the yield can be expected to correspond only to the product of the percentages of maximal yield of all three: $0.5 \times 0.75 \times 0.875 = 0.3281$, or 32.81 per cent of maximal yield. The percentage figure thus obtained has been termed the *fertility index.*[1]

Taken by itself the fertility index does not mean very much because the figures are ideal ones, presuming as they do that all other growth factors are at optimum which, in reality, they never are. But for a comparative study of the effects to be expected from fertilizers of different ratios, the fertility index is extremely useful in spite of its limitations.

Possible Yield from a Medium-Fertile Soil Without Fertilizer

The analysis of a natural loam soil of medium fertility may show, for instance, the following contents: 25 lb/acre of nitrogen, 50 to 60

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[1] Willcox, O. W., "The ABC of Agrobiology," W. W. Norton & Co., New York, 1937.

lb/acre of phosphorus (114 to 135 lb/acre of P_2O_5), and 100 to 140 lb/acre of potassium (120 to 165 lb/acre of K_2O). These are fairly common proportions in medium-heavy loam soils which have never been fertilized. Expressed in Baule units this would represent: 0.1 Baule of nitrogen, 2½ to 3 Baules of phosphorus, and 1½ to 2 Baules of potassium.[2] When the fertility index is applied to these figures, the following results will be obtained: $0.06 \times 0.82 \times 0.65 = 0.0320$ or 3.2 per cent[3] of maximal yield. This is extremely low because of the low nitrogen content, though the latter is somewhat deceptive since a soil of this type is usually able to maintain this level of available nitrogen throughout the season, as long as nothing but grasses and perhaps a few shrubs or trees grow on it. When it is plowed and a crop is planted on it, however, the low nitrogen level will definitely limit the yield.

Effect Produced by 5 Tons/Acre of Farm Manure

The farmer who takes such a soil into cultivation will—even without soil analysis and merely guided by experience—usually apply right away approximately 5 tons of manure/acre. Some more figuring will show what difference this is likely to make. In total, 5 tons of manure supply approximately 50 lb of nitrogen, 25 lb of phosphorus (as P_2O_5), and 50 lb of potassium (as K_2O) (see page 266) or, roughly figured in actually available amounts, 20 lb of nitrogen, 20 lb of phosphorus, and 40 lb of potassium. When this is added to the above, the soil will contain: 45 lb/acre of nitrogen, approximately 140 lb/acre P_2O_5, and 180 lb/acre K_2O, or in Baule units: 0.2 Baule of nitrogen, 3.1 Baules of phosphorus, and 2.0 Baules of potassium. The fertility index then will change to: $0.12 \times 0.88 \times 0.75 = 0.0792$ or 7.92 per cent, almost 8 per cent of maximal yield. This is still very low, but for a first crop the farmer may be satisfied. In the following year he is likely to conclude that he should now apply artificial fertilizer, which is perfectly true, but which places him before a fateful choice usually leading into error.

Result of Applying a Complete Fertilizer with a Wrong Ratio

Without soil analysis the farmer has no means of knowing that his soil is still pitifully low in nitrogen content, and, because he applied manure the year before, he is likely to conclude that he need not worry

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[2] 1 Baule of Nitrogen = 220 lb/acre of nitrogen; 1 Baule of phosphorus = 45 lb/acre of phosphorus pentoxide; 1 Baule of potassium = 82 lb/acre of potassium oxide.

[3] The percentages of maximal yield used in the fertility index can be computed from Table 34.2, page 360.

about the nitrogen. On the other hand, agricultural literature has made him very conscious of phosphorus and potassium which—contrary to fact—he believes to be generally low. Therefore, he is likely to choose a fertilizer with an analysis such as 4–10–8 or 5–10–13.

Effect of Fertilizer with the Analysis 4–10–8. Considering the losses of soil nutrients caused by the growing crop, by leaching, and by conversion into unavailable forms, the soil may be assumed to contain now approximately 25 lb/acre of nitrogen, 100 lb/acre of phosphorus (P_2O_5), and 120 lb/acre of potassium (K_2O). 1,000 lb of 4–10–8 fertilizer supply 40 lb of nitrogen, 100 lb of phosphorus, and 80 lb of potassium. Some of the phosphorus and potassium of the fertilizer will be "fixed" by the soil, which renders it more or less unavailable. How much is fixed in this manner depends on circumstances such as the type of soil involved, the amounts present, and the amounts added.

To counter objections to the figuring which follows, it may be assumed that 25 per cent of the added phosphorus and potassium become unavailable when entering the soil.

After deducting 25 per cent of the phosphorus and potassium, 1,000 lb of 4–10–8 fertilizer adds 40 lb of nitrogen, 75 lb of phosphorus (P_2O_5), and 60 lb of potassium (K_2O). The soil then would contain altogether in available amounts: 65 lb of nitrogen, 175 lb of phosphorus, and 180 lb of potassium. In Baule units this would be approximately 0.26 Baule of nitrogen, 4 Baules of phosphorus, and 2 Baules of potassium, and the fertility index would read $0.15 \times 0.9375 \times 0.75 = 0.14 =$ 14 per cent.

Cumulative Effect of Applying the Wrong Fertilizer. The farmer may be delighted with this increase and may even conclude that he has hit on the right kind of treatment for his soil. If he continues to apply this same fertilizer year after year, however, he will merely increase the nutritional unbalance, and further increases in yield will be unproportionately low. Phosphorus and potassium can be used by the plants only to a small degree, because nitrogen content is so low, and therefore both are bound to accumulate. After 3 years or more of applying 4–8–10 fertilizer, the soil is likely to contain still no more than 25 lb/acre of nitrogen, whereas phosphorus may have increased to 300 lb/acre or more, and potassium to 400 or 500 lb/acre. This is a highly undesirable unbalance, surprisingly common in the fields of truck or market gardeners. Not only is it wasteful, because these large amounts of phosphorus and potassium cannot be utilized in the absence of compensating amounts of nitrogen, but the unbalanced nutrition is likely to predispose the crop plants to diseases—first fungus and virus diseases and, in their train, insect pests.

This example shows clearly that fertilizer application cannot be based merely on experience, as is sometimes suggested. Without definite information on what is actually happening in the soil—which repeated soil analysis can supply—mere observation of results can lead one far and seriously astray.

Effect of Fertilizer with the Analysis 9–5–7. What would happen if, instead of the 4–10–8 fertilizer, the farmer had applied 1,000 lb of a fertilizer with the analysis 9–5–7, which likewise is commonly sold? The amounts contained in this fertilizer are 90 lb of nitrogen, 50 lb of phosphorus (P_2O_5), and 70 lb of potassium (K_2O). When again 25 per cent of the phosphorus and potassium are deducted as becoming more or less unavailable, the amounts added in available form will be 90 lb of nitrogen, 38 lb of phosphorus, and 53 lb of potassium. The soil then would contain 115 lb of nitrogen, 138 lb P_2O_5, and 173 lb K_2O. In Baule units this would represent: 0.5 Baule of nitrogen, 3 Baules of phosphorus, and 2 Baules of potassium, and the fertility index would read $0.3 \times 0.875 \times 0.75 = 0.1968$ or almost 20 per cent of maximal yield. This is a respectable amount more than was obtained with the 4–10–8 fertilizer, in spite of the fact that only about half the amount of phosphorus and even somewhat less potassium were applied.

Not only will this fertilizer produce a considerably higher yield without greater expense—all of these fertilizers cost the same—but phosphorus and potassium, being much more readily utilized because of the better balance, are much less likely to accumulate in an undesirable manner.

With the double amount or 1 ton of 9–5–7 fertilizer to the acre will be added (after deducting 25 per cent of the phosphorus and potassium):

	Nitrogen, lb	P_2O_5, lb	K_2O, lb
	180	75	105
plus the amounts present	25	100	120
The soil then contains	205	175	225

or approximately 1 Baule of nitrogen, 4 Baules of phosphorus, and 3 Baules of potassium. The fertility index then reads $0.5 \times 0.9375 \times 0.875 = 0.41$ or 41 per cent of maximal yield.

High-Analysis Fertilizer of Desirable Composition and Ratio

The same amounts of the three nutrients, added with 1 ton of 9–5–7 fertilizer, may be supplied with 1,000 lb of a fertilizer of the analysis 18–10–14, which may be composed of the following ingredients:

40 lb of ammonium nitrate (33 per cent) = 13 lb of nitrogen
19 lb of diammonium phosphate = 4 lb of nitrogen +
10 lb of phosphorus (P_2O_5)
14 lb of potassium chloride = 7 lb of potassium
13 lb of potassium sulfate = 7 lb of potassium
14 lb of milorganite as filler = 1 lb of nitrogen

100 lb, containing 18 lb of nitrogen, 10 lb of phosphorus, and 14 lb of potassium, or at the rate of 1,000 lb (and after deducting 25 per cent of the phosphorus and potassium), 180 lb of nitrogen, 75 lb of phosphorus, and 105 lb. of potassium.

To compensate the residual acidity of 1,000 lb of this fertilizer—when it is applied to a more or less acid soil—will require the simultaneous incorporation of 415 lb/acre of ground dolomitic limestone.

Though it will be an unquestionable advantage to be able to add the same amounts of plant nutrients with half the amount of fertilizer, it must be pointed out that, because of the ingredients used, 1,000 lb of the 18–10–14 fertilizer will be somewhat more expensive than 1 ton of 9–5–7 fertilizer. This must be taken into account, though with large quantities the reduced amount of sacking and the lower transportation costs will tend to offset the difference.

The inclusion of both milorganite and dolomitic limestone will assure the simultaneous incorporation of various minor elements, which always are more likely to become critical the higher the levels of nitrogen, phosphorus, and potassium are raised. This somewhat expensive fertilizer, therefore, will be worth its price also in so far as it will tend to create permanent fertility rather than a temporary boost likely to turn into exhaustion.

Maintaining or Raising Nitrogen Supplies Through Side Dressing

Even when 1 ton of 9–5–7 or 1,000 lb of 18–10–14 has been applied, there will still be considerable advantage in further raising the nitrogen supply by means of side dressings. One of the most satisfactory nitrogen carriers for this purpose is urea which—when applied twice at a 3-week interval and at the rate of 125 lb/acre[4] each time—will supply an additional amount of 116 lb/acre of nitrogen. This will raise the over-all nitrogen supply to 1½ Baules of nitrogen, and the fertility index then will read $0.625 \times 0.9375 \times 0.875 = 0.5126$ or 51¼ per cent of maximal yield.

In spite of the fact that the yield figures are ideal ones which, in

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[4] To compensate the residual acidity, 125 lb of urea require 95 lb of ground dolomitic limestone.

reality, cannot be reached, this kind of arithmetic is very intriguing. The results are eminently sensible, and even if one reduces the yield figures to half of their ideal value, because of the uncertainty of the other growth factors, they still make sense. Field trials with fertilizer applications in accordance with these figures show clearly that they cannot be very far wrong.

The implication that it is worse than useless to apply fertilizers with a high content of phosphorus and potassium when nitrogen is neglected is certainly worth heeding. Soil supplies of nitrogen are nearly always low.

39. THE IDEAL SOIL NUTRIENT BALANCE AND THE CORRECTION OF AN UNBALANCED SOIL

The final consequence of the computations in the preceding chapter consists in attempting to determine what constitutes the proportion between nitrogen, phosphorus, and potassium which one should strive to provide and to maintain in the soil.

Again this is tentative, and the main value of what follows consists in the fact that it provides a means of cross-checking. The basic soil balance, according to the principles outlined above, would be an equal number of Baules of nitrogen, phosphorus, and potassium, producing the basic ratio 5–1–2. As was explained, this cannot be carried very far, because it is impossible to supply more than 1½ to 2 Baules of nitrogen. The most nearly normal proportion would be 3 Baules each of phosphorus and potassium for each Baule of nitrogen, resulting in the approximate ratio of 2–1–2 or its multiples 6–3–6, 8–4–8, 10–5–10, etc.

Most soil scientists will object to these proportions and will point out, justly, that they can be used only under certain specific conditions such, for instance, as when tobacco is to be grown on sandy loam soils. This is undoubtedly true. The figures are given here only in order to show the logical consequence of the purely mathematical approach. The latter certainly can serve as a guide, and it does bring into focus the importance of the much-neglected nitrogen. Especially in its ultimate consequence, it becomes questionable; there is no doubt, however, that the establishment of an "average" ideal proportion between the three major nutrient elements, which would be applicable under average circumstances, would be extremely helpful. Most likely this will be in the neighborhood of the ratio 9–5–7 or its multiple 18–10–14.

Procedure for Correcting Soil Unbalance

Once such an average ideal proportion is established, the logical procedure in soil fertility correction would be to raise the soil content, as determined by means of soil analysis, to a near-balance. This can be accomplished by applying first single fertilizers supplying the required amounts of either nitrogen, phosphorus, or potassium, whichever may be too low. After this initial step, the nutrient balance can be maintained and the general fertility can be raised through application of a fertilizer with a properly balanced ratio, such as the tentatively proposed 9–5–7.

Nitrogen supplies can be maintained by means of side dressing or by applying urea-form or "Uramite" at the beginning of the season.

PART VII

Summary of Scientific and Practical Procedures

INTRODUCTION

The Mitscherlich principles, as outlined in Part VI, are becoming ever more widely recognized as a valuable aid and are employed in basic computations or for cross-checking by most of the leading American soil research institutes and laboratories. They are widely applied also in several countries of Europe.

The main objections to a purely mathematical approach in the study of soil fertility center on the following four points:

(1) The fixing power of the soil, especially for phosphorus and potassium, which varies with different types of soil. This means that, depending on soil composition and texture, the same amounts of phosphorus and potassium fertilizers will give different results, because different proportions of these nutrient elements will become unavailable as soon as they enter the soil.

(2) The action of the various minor elements which is still only partly known and which likewise differs in different types of soil. The interference or interaction of these minor elements with the major elements varies with the condition of the soil and with climate.

(3) The physical soil condition which influences the ability of plants to utilize the various nutrient elements, and the fact that the most favorable physical soil condition varies with different crop plants. Under field conditions only minor modifications of physical soil condition are possible, and, in most instances, it will be necessary to choose crop plants which prefer, or at least tolerate, the prevailing conditions.

(4) The variation in what constitutes a satisfactory level of the major nutrient elements for various types of crop plants which is well apparent. Peanuts and lespedeza, for instance, are known to be able to absorb adequate amounts of potassium at much lower soil potassium levels than can alfalfa or soybeans, which also are legumes. The possibility of avoiding needless expense for fertilizers will always have to be considered.

These points, which have become apparent in the course of extensive field trials, have led to empirical procedures which are guided largely by constant observation, and which employ the mathematical formulas of

Mitscherlich and others mainly as a cross-check. The main soil groups are classified according to their fixing power for phosphorus and potassium—depending on soil colloid content—as well as to physical condition, and recommendations for fertilizer application then are based mainly on economic expediency. The concept of ideal soil fertility serves only as control, setting the limits to which an unbalance may be carried.

The following chapters provide a description of the means employed in checking plant efficiency in nutrient utilization, as well as of the various factors which are taken into account in the judging of soil fertility and in the recommendations made for increasing yields within economical limits. The final chapters give a summation of practical procedures for soil improvement under special conditions. Though partly repetitious because it is based on previously explained facts, the information given in these final chapters should prove helpful to the practical grower.

40. PLANT ANALYSIS AS AN AID IN EVALUATING SOIL NUTRIENT BALANCE

It seems reasonable to suppose that the proportion of the various required nutrient elements which should be present in the soil could be established most readily by analyzing the contents of the plants themselves. Unfortunately, this is not the case because of the complexity of the processes involved.

Not only must the amounts of the nutrient elements in the soil always be considerably larger than those which the plants require and remove, but even the ratio of the elements to each other cannot be expected to coincide in the plants and in the soil. In addition, plants are likely to absorb more of one element and less of another than they actually require for best development, in spite of both being readily available in the soil. (See page 246.)

Many valuable conclusions, however, can be drawn from plant analysis when it is coupled with soil analysis. It then becomes possible to judge the efficiency of nutrient element absorption, not only of the same kind of plant from different types of soil but also of different types of plants, or even of different races of the same plant from one particular type of soil.

Neubauer Seedling Method

One of the most promising procedures for the experimental study of plant nutrition is the Neubauer seedling method. This is based on the principle of intensive nutrient uptake through a large number of seedlings growing in a limited quantity of soil. The root systems of the plants thoroughly penetrate all of the soil, and the proportion of the nutrients present which can be absorbed becomes quickly exhausted. Through chemical analysis of the plants, it is then possible to determine the amounts of the various nutrient elements contained in a certain quantity of plant material, which can be compared with the amounts known to have been present in the soil originally as well as with the available amounts still left in the soil after conclusion of the experiment.

The details of the procedure will not be outlined here,[1] but it may be emphasized that careful control is required in order to avoid errors. One of the critical factors is water, which must be supplied to all pots in absolutely equal amounts. Any irregularity in watering will result in deviations which may render the whole experiment valueless. The amount of light to which the plants are exposed must likewise be strictly controlled so that it is the same for all.

Tissue Tests and Soil Analysis Together as Aids in the Field

A combination of plant and soil analysis—or tissue tests[2] and soil analysis—is extremely useful also in the field, where it offers one of the most satisfactory means of establishing scientifically the reason for a certain deficiency. Often, only when soil and plants are studied together and in comparison with each other will it be possible to find out what is wrong and what remedial measures are most likely to lead to success.

Radioactive Isotopes

Since the advent of artificial radioactive isotopes of the various elements used by plants in their nutrition, great progress has been made in the understanding of the elements' relative importance. The word "isotope" comes from two Greek words: *isos*—equal or same, and *topos*—place, signifying that the isotope of an element occupies the same place in the periodic table as the element itself. The isotope is identical in chemical behavior. It differs only slightly in atomic weight but very importantly in the fact that it is radioactive. The radioactivity of the isotope makes it possible to trace its path through the tissues of the plant, thus enabling the researcher to establish clearly to which parts of a plant a certain nutrient element is transported. Subsequent analysis of the plant even determines what specific purposes the element serves in the various parts and organs of the plant, because the radioactivity of the isotope makes it possible to identify it even after it has become part of a complex compound.

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[1] Diagnostic techniques for soils and crops, Editor H. B. Kitchen, Am. Potash Inst., Washington, 1948.

[2] Lundegardh, H., Die Blattanalyse (transl. Mitchell, R. L., Leaf Analysis, Hilger & Watts Ltd., London, 1951).

The efficiency of uptake of the nutrient elements by various plants from different soil types can be studied in the same manner. Being much more precise than ordinary plant analysis, this type of research can quickly reveal, for instance, exactly where in a plant's body a certain element may have been precipitated, preventing it from moving on to the place where it is most needed. The reason for the precipitation, which refers back to the soil, can then be established by chemical plant and soil analysis.

41. THE PREFERENCE OF CERTAIN PLANTS FOR CERTAIN NUTRIENTS

It is commonly believed, and sometimes even stated in agricultural or horticultural literature, that certain crop plants have a distinct preference for one or the other of the "big three" nutrient elements—nitrogen, phosphorus, or potassium. Expressed in this manner the statement is wrong, or at least highly misleading, as will be explained below.

Crop Plants Grouped According to Response to the Three Main Nutrient Elements

The following grouping, which is frequently quoted, becomes applicable only if one drops the word "preference" and rewords the statement to say that certain crop plants *respond more readily* to an application of one of the three most important nutrients than to that of another.

✓(1) Leafy vegetables, such as cabbage, kale, cauliflower, and kohlrabi, as well as fodder rye grass, sorghum, and corn (maize) for silage, are known as nitrogen consumers for which the application of manure or of commercial fertilizers high in nitrogen content is advised.

✓(2) Grain crops or cereals, such as wheat, oats, barley, and rye, are believed to require, in particular, adequate supplies of phosphorus and potassium, and the farmer is warned not to apply large amounts of nitrogen, since this might cause "lodging."

✓(3) Potatoes, tomatoes, cucumber, squash, pumpkins, mangold, and sugar beet are generally recognized as heavy feeders, requiring a high general soil-fertility level, with emphasis on potassium for potatoes and on phosphorus for tomatoes and cucumber.

✓(4) Turnips, swedes, and carrots are considered to be most responsive to phosphate, with nitrogen and potassium being of less importance. Sometimes it is claimed that carrots, in particular, require relatively large amounts of potassium also.

This grouping results partly from a misinterpretation of the reaction to different soil types (especially paragraphs 3 and 4) and partly from a misunderstanding of what constitutes a favorable soil nutrient balance. It is not without merit, however, and can be used to advantage when the following facts are taken into account.

Modification of Crop Plants Through Centuries of Cultivation

All of the plants enumerated above have been greatly modified through centuries of cultivation for the special use of man. This modification has tended to favor the abnormal development of certain specific parts of these plants—leaves, grains, fruits, or roots—depending on which part serves as food. In consequence, the plants do not respond in the same manner to an unbalanced soil supply of nutrients.

Effect of Different Nutrient Levels on Different Crop Plants

For instance, a soil which is low in nitrogen content is bound to give poor results with leafy vegetables because they must have a sufficient supply of nitrogen to be able to make efficient use of phosphorus and potassium, all of which are required for the luxurious development of leaves. A low nitrogen supply, therefore, will be felt very severely by this particular kind of crop.

With rye or barley the same soil will produce a fairly good crop, as long as phosphorus and potassium supplies are adequate. As was pointed out in Part VI, yields continue to increase even when only the supplies of one or two of the three main nutrient elements are raised beyond what constitutes a balance. This increase, as is now evident, is more pronounced with one type of crop plant than with another.

A surplus nitrogen supply—beyond the amount which would balance the available amounts of phosphorus and potassium—can occur only when the soil content of phosphorus and potassium was low to start with and when only nitrogen fertilizer has been applied. Such a condition will not seriously affect the leafy vegetables as long as the unbalance is not too pronounced, but it is bound to cause trouble with grain crops. Because of the relative abundance of nitrogen, the latter are unable to make efficient use of the inadequate supplies of phosphorus and potassium which are required for seed development. Grain crops, under such circumstances, will produce strong stems and relatively large leaf surfaces, but their grains are likely to "lodge." The difference in the reaction of these crop plants, therefore, represents not a preference for one or the other of the three main nutrient substances but a difference in tolerance to unbalance. Whatever emphasis there is on a certain nutrient element, which must not be too low in proportion to the others, results from favoring the development of one particular part of the plant.

Effect of Fertilizer Application According to Presumed Plant Preference

Because wrong fertilizer practices by farmers are unfortunately common and often are continued for many years without control through soil analysis, the supplies of nutrient elements in cultivated soils frequently are unbalanced. In consequence, the difference in tolerance of the various crop plants is readily observable everywhere. This has given rise to the above-mentioned belief in a pronounced preference.

Formerly cultivated fields in the immediate outskirts of cities—which, because of rising real-estate values have long been abandoned and now await the steam shovel of the building contractor—frequently show a very beautiful soil balance. The latter has re-established and maintained itself under the cover of volunteer grasses. An analysis, such as 125 lb/acre of nitrogen, 100 lb/acre of phosphorus (P_2O_5), and 150 lb/acre of potassium (K_2O), is quite common on average loam soils in such abandoned fields. With such a soil it would be extremely easy to raise the fertility level in proper balance, as high as economic limits permit, and to maintain this level by replacing every year the amounts of the various nutrient elements which have been removed. The latter can be established through soil analysis. But when a market gardener takes over such an abandoned field, wrong fertilizer practices, based on the mistaken belief in plant nutrient preferences, usually upset the balance completely within a few years. The result is that neither yield nor crop quality are what they could easily have been and that troubles with diseases and insect pests multiply.

The judicious use which may be made of the tolerance of certain plants to certain types of unbalance, in order to save fertilizer, will be explained in the following chapter.

Presumed Preference of Potatoes for Potassium

The common belief that potatoes are most in need of potassium probably derives from the fact that potatoes are generally grown on light sandy loam soils or on light humus soils which frequently are low in potassium content. Such soils are by no means always low in potassium content, however, and, besides, potatoes are raised also on clay loams which, by nature, may be quite rich in potassium. To add further amounts of potassium to such a soil will be a waste of expensive fertilizer, because it will not produce a proportionate increase in yield and profit. Soil analysis is likely to indicate that another fertilizer would be much more profitable by establishing a near-balance and, therewith, noticeably raising yield or quality or both.

Influence of Nitrogen on Flowering

This discussion of nutrient balance may be concluded by mention of yet another phase which concerns the influence of nitrogen on the flowering of plants. It has been known for some time that, though many plants are little or not at all affected in the time of their flowering by a high nitrogen level, quite a few react to an unbalance in favor of nitrogen by flowering later or earlier. Recent investigations[1] tend to show that the main difference in reaction is between long-day and short-day plants, viz., those which normally flower during the long days of early summer and those which flower during the shorter days of autumn. The former, such as barley, hard wheat, spinach, lettuce, iberis, and some forms of marigold, flower later when the nitrogen supply is high, whereas those of the second group, such as soybean, chrysanthemum, kalanchoe, tithonia, and *Salvia splendens,* flower earlier at a high nitrogen level. This reaction to an unbalance may well be utilized as a contributing factor in efforts to hasten or delay the flowering of any of these plants, whenever this is desired for special purposes.

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[1] Withrow, R. B., Chap. 16 in Truog, E., "Mineral Nutrition of Plants," University of Wisconsin Press, Madison, Wisconsin, 1951.

42. PROCEDURES OF THE MODERN SOIL SCIENTIST

Factors Which Guide Recommendations of a Soil Specialist

The modern soil scientist, when called upon for advice, takes into account all that has been treated previously in this text, including the Mitscherlich computations modified according to the four points mentioned on page 384. He will consider the aeration and the water-holding capacity of the soil, the organic-matter level, the rate of nitrogen transformation to ammonia and nitrate, the effect of different types of fertilizers on the yield and quality of different crop plants, the cost of fertilizers in comparison to the increase in profit which may be expected, and the climate, especially in regard to amount of rainfall, temperature, and length of growing season. Management practices which, by themselves, can often contribute materially to increased profits will come under his scrutiny also, and he will extend his investigation to include the various factors which may mask the effect of fertilizer application. The most important of the latter are deficiency in a minor element—often detectable visually by discoloration of the leaves in characteristic patterns—nematodes, or other soil pests, and biological conditions, such as proper soil inoculation for a legume crop. All of these points have been covered in detail in other parts of this book.

Virus diseases and other epidemic infestations, which have not been included in this book but which likewise interfere with normal nutrition, must be considered also.

Information to Be Supplied by the Farmer

For such a preliminary investigation the farmer must supply the history of the field under study and must furnish information on the previous treatment of the soil, including fertilizer or green manure applications, the types of crop plants which have been raised over a period of years, and the yields they have given. A chemical analysis of the soil cannot make much sense without this information.

Practical Application of Plant Tolerance to Unbalance

The recommendations of the specialist for future soil treatment are based preferably not on 1 year and 1 crop but on a sequence of crops in a rotation program, extending over a period of 8 to 10 years. In such a sequence, full advantage can be taken of the tolerance of the various crop plants to unbalance, in order to save fertilizer. The economics of agriculture cannot be neglected, and if a push to one side of the balance produces a greater increase in yield with one crop plant than with another, this must be utilized. To raise the whole balance in proportion, though it would produce still higher yields or higher quality, may be too expensive in comparison to the increase obtained. In a crop sequence the emphasis, therefore, is shifted from one nutrient element to another, depending on which crop responds most profitably to a specific unbalance. This procedure is perfectly safe, as long as one knows exactly what one is doing and stays within the limits in which the unbalance works.

The farmer is on dangerous ground if he tries to do this by guessing about it, because only repeated soil analysis and tissue tests can make sure that one stays within bounds.

Advantages of a Re-examination After Fertilizer Application

Even the soil scientist, because of the many uncertainties involved, may need to recheck before the crops are harvested in order to make sure that his recommendations were the very best possible, and he should be given a chance to do so.

Uncertainties include not only the soil itself—such as the action of the various soil colloids which often can be judged properly only after the recommended fertilizer has been applied and plants are growing on the soil—but also the time of year or the period within a plant's seasonal growth at which the application of fertilizer is most effective and, therefore, most profitable. The latter depends largely upon the type of crop which is being raised but is very much influenced also by the physical condition of the soil and by climatic conditions. The recheck by an expert before the first year's crop is harvested may, therefore, result in a recommendation of fall instead of spring application of fertilizer, or vice versa. The advantages of row application over broadcast application, deep or shallow application, liquid or dry application, foliar application, and side dressing or top-dressing can always be evaluated most efficiently by means of a re-examination.

Effect of Supplementary Fertilizer Application on Different Crop Plants

The seasonal difference in the effect of supplementary fertilizer application on different crop plants must be considered also. It has been found, for instance, that carrots absorb, during the first 70 days after germination, only about 4 per cent of the total nutrient elements they contain at maturity. During the next 27 days 27 per cent are absorbed, and 69 per cent during the rest of the growing season. The most active period in the life of an oat plant, on the other hand—the period during which it absorbs most of the nutrient elements it uses—is from the seventh to the ninth week after germination.

This is an extremely useful type of research which will undoubtedly be farther extended in the future. With this kind of information it is possible to time supplementary fertilizer applications in such a manner that the most efficient use is made of even small amounts. Considerable savings may thus be made, especially with soils which are subject to leaching or which have a high fixing power for phosphorus and potassium.

43. IMPROVING THE PHYSICAL CONDITION OF A SOIL

DISADVANTAGES OF COMPACTED SOIL

The depth of the topsoil, as pointed out previously, is an important growth factor. (See page 372.) As was shown, yields increased with increasing topsoil depth, though this resulted mainly because, in this sense, the conception "topsoil" includes a favorable structure of just the right degree of porosity. A soil may be deep, and it may be rich in all the required plant nutrients, but it will still produce no more than medium to low yields when it is compacted to such an extent that the free movement of air and water is impeded. (See page 97.)

CULTURAL METHODS TO PREVENT SOIL COMPACTING

This, then, is the reason why mechanical loosening of the soil through the right type of plowing is, and will remain, unavoidable. This is why fall plowing, leaving the furrows rough over winter, is so advantageous with a heavy clayey soil, because through frost action this leads to an improvement of the soil structure. This is why hoeing or some other type of cultivating must not be neglected with any type of soil containing a fair amount of clay—not only for the sake of removing weeds but also because it breaks the puddled surface crust which otherwise is sure to form. On the other hand, one should realize that hoeing and cultivating can be overdone also. In general, soil cultivation is necessary only as long as the plants are small. Whether it is worth while to continue cultivating once the crop plants are large enough to shade the soil is rather doubtful. At any rate, such cultivation should always be shallow, since deep cultivation is not only likely to injure the roots but may actually damage the soil. How often one should cultivate depends upon the type of soil and the type of crop plant.

Specific Instances of Importance of Proper Soil Aeration

The main reason why potatoes and other tuberous plants give best results in a light sandy soil or a light humus soil, and why they have to be hoed frequently and hilled at the same time, is that, in a heavy compacting soil, these plants cannot muster the energy to push the soil particles away so as to make room for their tubers.

Artificial soil aeration with compressed air will often be the only means of saving valuable trees growing in the heavily compacted soil of city streets or on popular picnic areas. The means which may be employed to assure aeration when soil is filled around existing trees were described on page 97.

Naturally, it is not possible to restrict the raising of crops entirely to those soil types which, because of their natural physical condition, are most suitable for the purpose. The time when this could be done is long past, and in future it will become ever more necessary to utilize soils which have to be conditioned first before they can produce high yields.

SOIL AGGREGATION (CRUMB STRUCTURE) AS A GROWTH FACTOR

The physical conditions most favorable for plant growth are unquestionably represented by a well-aggregated soil. (See page 118.) The loose crumbs can be compacted only through pressure, such as trampling, and by water only when it hits with sufficient force to shatter the crumbs (on the soil surface). As long as the crumbs are intact, the movement of air and water, the exchange of nutrient ions from colloids to soil solution (and vice versa), the activities of the soil microorganisms, and the development and extension of roots are all as free and unhindered as they can possibly be. Several important growth factors are thus given a chance to become as fully effective as the climatic conditions, which are beyond our control, permit. Any efforts, therefore, toward producing, improving, or maintaining soil aggregation are very much worth while.

The main factors which are responsible for a good crumb structure may once more be summarized as follows: (1) a soil pH value between 6.0 and 7.2, (2) a favorable clay and humus content (well proportioned), (3) a favorable level of calcium content (medium high), and (4) a favorable moisture content (reasonably stable—not too high and not too low). (See also page 123.) These requirements point the way to possible procedures for improvement.

HOW TO IMPROVE THE PHYSICAL CONDITION OF DIFFERENT SOILS

An acid clay soil, for instance, can be improved through the addition of proper amounts of ground limestone and manure or neutral peat moss. If it is too wet, it must be drained. The addition of a certain amount of sand may be helpful also, depending upon the type of clay, but this must not be overdone, since sand grains can be included in a soil aggregate only when they are fine enough, when there are not too many of them, and when they are covered with a film of clay.

An acid organic soil can be improved through the addition of ground limestone and clay or through the incorporation of marl, when this is available in the subsoil. Drainage is as important here as with a heavy clay soil.

An acid sandy soil requires clay, lime, and organic matter. Marl with manure or with a neutral peat moss will be most effective.

An alkaline clay soil in regions with normal annual rainfall (over 20 in.) can be improved through the addition of acid peat moss and flower of sulfur. (See page 415.)

Long-Range Policy for Improvement of Large Areas

As is apparent from these condensed directions, an actual change in the physical condition of a soil involves not only proper planning based on knowledge of the soil but, unavoidably, also a certain amount of expense. Costs must be carefully calculated before one proceeds with a large-scale amelioration scheme, and, where hundreds or perhaps even thousands of acres are concerned, one will have to evolve a long-range policy for gradual amelioration over a period of many years. A correct rotation of crops, adjusted to the specific soil type and including rest periods under pasture or hay as well as well-spaced incorporations of green manure (page 189), must take an important place in any such undertaking. The proper choice of crop plants which will not exhaust the soil faster than it can be improved will become a vital consideration.

Methods for the Private Gardener

In the home garden, where only a limited area is concerned, even radical changes in physical soil condition are perfectly feasible, as long as one is not afraid of the required labor. The compost pile (page 273) then assumes a high importance; where peat moss is employed, one must make sure to choose an acid peat moss for an alkaline soil and a neutral peat moss for an acid soil.[1] Compost likewise may be made more or less acid or alkaline or neutral, depending upon the purpose or the type of plant or soil for which it is to serve. The type of material set up for decomposition, the type of fertilizer used, and the addition or omission of ground limestone will regulate the pH value of the finished compost. It is important to realize, however, that the more acid a compost is, the more slowly and the less completely will it decompose.

The truck or market gardener who operates on a few acres must spare no effort to raise the physical condition of his soil to the highest possible perfection. The higher quality and the earlier and more abundant harvest which he will thus achieve without higher costs for fertilizer will recompense him many times over for his labor. (See page 372.)

Synthetically Produced Soil Conditioners

Where good soil aggregation develops naturally or through correct adjustment of the pH value and the composition of the soil, it is usually also most stable, but, even under such conditions, frequent cultivation tends to shatter the soil crumbs, especially near the surface. Under continuous cultivation extending over several years, without rest periods under pasture or hay, the best crumb structure is likely to deteriorate gradually. Besides, there are vast areas throughout the world where climatic conditions work against a stable crumb structure and where, no matter what one may do, the soil aggregates will always remain fragile and short lived.

How a Soil Conditioner Acts. These facts lend considerable interest to the artificial soil conditioners, of which the much-advertised "Krilium" and "Aerotil" appear to have been the precursors. "Krilium," as well as all the other similar materials sold under numerous trade names, is a synthetic resin compound which does not, by itself, create soil aggregation. It merely renders existing soil crumbs more stable than they would have been without it, and it makes it possible to create, through proper cultivation, stable aggregation in a soil which, without the addition of a conditioner, would have compacted itself again shortly after being cultivated. The benefits deriving from an application of "Krilium" or any of the other similar soil conditioners result solely from improved physical conditions. Soil nutrient content and soil organic-matter content retain their full importance, but this does not change the fact that the benefits of improved physical condition can be very considerable.

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[1] Imported European peat moss usually is neutral in reaction, whereas American and, especially, Canadian peat mosses usually are more or less acid.

Limits and Advantages of a Soil Conditioner. Naturally, it is not worth while to apply an artificial soil conditioner to a soil which cannot produce a crumb structure because it lacks the type of soil particles which can aggregate. On sand or peat, for instance, the soil conditioners will have no effect. Neither do they work with pure clay or with all types of clay.

One of the greatest advantages of the synthetic soil conditioners is that they are not subject to decomposition by bacteria, as are the organic glues (page 121) which fulfill the same function in a naturally aggregated soil. In consequence, the soil conditioners remain effective for a number of years, and annual application is neither necessary nor desirable. Mass production of these conditioners will probably bring their price within everyone's reach, so that eventually they may assume a rather important place in general soil amelioration, in the fight against soil erosion, and in the increase of crop yields.

Soil Conditioners in Greenhouse Gardening. "Krilium" or other soil conditioners will probably prove very helpful also on greenhouse benches, especially in the culture of certain plants which require a fairly heavy soil, such as chrysanthemums. Because of forced feeding combined with frequent watering, such a clayey soil is inclined to compact more and more—especially toward the end of the culture period—therewith limiting the efficiency of the plant nutrients, and the incorporation of a soil conditioner which is able to maintain a loser soil structure should prove distinctly beneficial.

The amount of conditioner which should be applied to obtain best results varies somewhat with the type of product employed and depends, by necessity, to a certain extent also on the type of soil involved. This will not be elaborated here; one should simply follow the directions given on the package. Thorough mixing with the soil, preferably by means of a mechanical tiller, is very important. The soil must be reasonably dry to make thorough mixing possible.

44. CONTROL OF THE WATER SUPPLY

Since water is an important link in the chain of factors which influence plant nutrition (see page 367), the ways and means which may be employed to assure cultivated plants of an adequate water supply may be further elaborated.

Estimating Cost and Profit of Irrigation

The installation of an artificial irrigation system is costly, especially when sufficient or suitable water is not available in the immediate vicinity; thus the investment will pay dividends only if the increase in yield which can be expected is sufficiently high to pay for the cost of installation and provide a profit as well. It is mainly for this reason that the largest investments in artificial irrigation are generally made in arid or semiarid regions, which would be worthless without water but which, with irrigation, can be made extremely valuable. Rice—one of the most important grain crops of the world—is an exception, requiring rather elaborate irrigation layouts even in the humid regions where most of it is grown. The suitability of the climate for more or less continuous cultivation the year around is an important consideration also, since an expensive installation with water piped in from a distance can hardly be worth while if the raising of crops is possible for only a few months of the year.

Factors Decisive for the Feasibility of Irrigation

Other important points which must be investigated when the large-scale irrigation of an arid or semiarid soil is considered are the following: the physical condition of the soil and its ability to hold water, specifically the speed with which it permits water to drain through; the amount of salt (especially sodium) the soil contains; the general topography, as far as it influences the ready and even dispersal of the irrigation water; the amount of water which can be made available; and the quality of the water. Whether a relatively high salt or silt content, or both, of the irrigation water will be harmful, more or less unimportant, or, within limits, perhaps even beneficial depends upon the kind of soil to be irrigated as well as on the kinds of salts the water may contain.[1]

Native Plants as Indicators of Salinity. In the preliminary survey of a more or less arid region to locate the most suitable areas for large-scale irrigation, the native flora can often serve as indicators of soil salt content. This cannot take the place of a thorough scientific investigation, which must be carried out anyhow, but it will be helpful. Soil analysis, as well as the use of various types of special apparatus to measure not only the total salt content of the soil but also the amount of water which will be required to produce satisfactory results, will complete the survey.

Most of the above problems enter the picture only in regions with an annual rainfall below 10 or at most 15 in., and, since excellent literature on this special type of agriculture is available,[2] this subject will not be treated here in further detail.

Irrigation in Humid Regions

In large parts of the world, where natural precipitation is, in general, sufficient for crop raising without irrigation, water supplies may become critically low for 2 or 3 months during the height of the growing season. Irrigation during these periods may make a very big difference in the development of the plants, and it will then become necessary to weigh the expense involved against the value of the crop plus the increase in yield and the improvement in quality which may be gained.

Sodium Content of Well Water

One fact which must be emphasized is that water from wells may have an undesirably high sodium content. This may occur almost anywhere, and is by no means limited to arid or semiarid regions. Since this

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[1] Recent experiments, carried out in Israel, using sea water for the irrigation of seaside dune sand appear to be very promising. It was found that, providing the sand or gravel used as a growing medium contained no more than small traces of clay substance (2 per cent), the sand or gravel was at least 6 to 8 ft deep, and good subsoil drainage was assured, irrigation with sea water produced satisfactory results with a number of crop plants. These experiments, which still have to pass the test of field application, suggest that sea water, as long as the plants themselves are not wetted with it and provided that soil conditions are suitable, is definitely not as detrimental to crop plants as has been generally assumed. (Boyko, H., and Boyko, E., (Israel), "Seawater Irrigation," *Int. J. Bioclimatology and Biometeorology,* Vol. III, Part II, Sect., B_1, p. 3. (Leiden, 1959).

[2] Thorne, D. W., and Peterson, H. B., "Irrigated Soils," 1949.

may have serious consequences, it is always advisable to have well water analyzed for sodium content before it is used for irrigation. A water sodium content below 60 per cent is generally considered harmless, as long as it is not sprayed on the leaves of the plants and if the soil contains a fair amount of calcium. Sodium-containing water will be most objectionable where poorly drained clay soils are concerned.

Soil Moisture Conservation

Another equally important point is that wherever water is or may become a critical factor, all possible means must be employed to conserve soil moisture, regardless of whether irrigation is practiced or not. For this purpose a favorable soil organic-matter content and a good physical condition of the soil (soil aggregation) will be particularly helpful. Since weeds not only compete with the crop plants for the soil water but also contribute very measurably to the loss of water to the air through evaporation, weeds must not be tolerated.

Covering of the soil surface between the plants with a mulch or other material should be considered wherever a high-value cash crop can justify the additional expense. Since such a surface covering may make irrigation unnecessary, it should be decided for each case which procedure will be the least costly or the most efficient.

Subsoil plowing must enter this picture also, since it may be required to assure satisfactory penetration of either irrigation or rain water, demonstrating once again the interdependence of the various growth factors.

Hedgerows and Windbreaks. That any kind of wind—even the mildest—will greatly increase evaporation and thus cause the loss of precious soil water should need no emphasis, but it is frequently disregarded in measures to conserve soil moisture. The farmer is inclined to believe that hedgerows are a nuisance, occupying valuable space which could be used for crop raising. The facts are that windbreaks or hedge plantings, properly spaced and oriented at right angles to the prevailing wind direction, can and do produce such pronounced increases in yield—by cutting down the air movement immediately over the soil surface—that the space they occupy is immaterial. (See also page 185). Especially the market gardener, who practices very intense cultivation, will derive such great benefits from hedgerows that he should never omit them.

Shrub Propagation by Layering with Soil Moisture Control. How decisive soil moisture control can be for plant growth is most evident in plant propagation. Dutch nurserymen, for instance, are famous for the certainty and ease with which they manage to propagate a large variety of shrubs by layers, a method which has not been generally successful in North America. The procedure consists in lining out the mother plants in rows, cutting them down to ground level, and then bending the young shoots which are produced in an ~ curve, so that they are partly buried all around the mother plant with only the tips sticking out. One-year-old shoots layered in early spring are rooted and ready for removal by fall. The main secret of success is a very even and unvarying soil moisture content to approximately 50 per cent of saturation. This is achieved through control of the ground water table by means of canals. When the ground water table threatens to rise higher than desirable, the canals are opened for drainage, and when it sinks so low that the soil is likely to dry, the canals are closed to hold the water at a higher level. This highly efficient system demonstrates how special conditions can be utilized to control soil moisture with the least possible expense.

Subirrigation in the Greenhouse. Specially constructed greenhouse beds for the rooting of cuttings, or concrete benches for the subirrigation of potted plants, work on very much the same general principle and have been found highly satisfactory.

Nutrient Content Increases Effectiveness of Water

One other example may be given which shows clearly how the effectiveness of water depends upon, and is proportionate to, the active amounts or quantities of the other growth factors present. (See also page 369.)

Establishing a Lawn on Poor Sandy Soil. When a lawn has been established on a sandy and easily draining soil, it will not be long before it shows unmistakable signs of suffering from drought. Heavy watering is likely to make matters worse by leaching out the low amounts of plant nutrients which such a light soil usually contains. The application of commercial fertilizer is not likely to be of much help either, because the frequently required watering will wash most of it away before the grass roots can utilize it. One may, of course, rip up such a lawn and condition the soil through the incorporation of large amounts of organic matter before reseeding it, but this is very costly. The most efficient procedure is to apply fertilizer and water simultaneously. Special attachments for hose or sprinkler are available in which dissolved fertilizer may be placed, so that the water carries the fertilizer along at an even rate. Such dissolved fertilizer is absorbed by the plants very quickly—even the leaves absorb some of it—and comparatively little of it is lost with the drainage. With a light sandy soil, the effect of liquid fertilizer is approximately three times that of solid fertilizer, or, in other words, only one third as much is required for the same effect. If this treatment is continued, a very fine lawn may be established even on a poor sandy soil, and, the longer the grass cover is maintained, the more will the soil beneath it improve by being gradually enriched in humus. Watering as well as feeding then will be needed much less frequently. Occasional light top-dressing with a good humus soil to which some fertilizer has been added will be helpful also.

Liquid Fertilizer in Irrigation Water. What applies to a lawn is true likewise for other plants or crops, and, wherever irrigation is practiced, the application of fertilizer with the water—in proper balance according to soil condition—should be considered. Such a procedure saves not only fertilizer but water also, because plants can subsist on less water when they are properly nourished. (See page 370.)

Sprinkler Irrigation

In regions which are not level enough or cannot easily be leveled sufficiently to make surface irrigation by means of ditches possible, overhead irrigation with sprinklers offers a ready solution. Several hundred thousand acres altogether are being sprinkler irrigated in various parts of the United States alone, a surprisingly large part of this acreage being located in nonarid regions (Oregon, Washington, New Jersey, Michigan, Wisconsin, and Massachusetts). Naturally, it will always be most unwise to install an expensive sprinkler system on the basis of a guess. The advantage which may be gained from such an investment, as well as the amount of water needed and the type of sprinkler system which will serve best and most economically, must be thoroughly studied in advance.

45. THE CONTROL AND IMPROVEMENT OF THE pH VALUE OF AN ACID SOIL

Components of the Acid Soil Complex

The various substances as well as the chemical and biological processes which are responsible for soil acidity were discussed in Part II (pages 106-9). They are commonly gathered together under the descriptive term *acid soil complex,* because theirs is a combined action. They may be enumerated as follows:

(1) *Various inorganic acids,* especially sulfuric acid but to a certain extent also hydrochloric acid and nitric acid which are formed in strongly acid bog soils (pH 3 to 4) through the hydration of iron, aluminum, and manganese salts. (See page 233.)

Free carbonic acid is most likely to be present at a pH value between 5 and 6.5 but is too weak to have much of an effect on the soil reaction. It is responsible, however, for the formation of bicarbonates—especially calcium bicarbonate (with a pH of 6)—which is importantly involved in the stabilization of the pH value near the neutral point as well as in the conspicuous slowing down of the pH rise near pH 6 when ground limestone is applied to an acid soil.

(2) Certain organic acids, especially humic acid which, when pure, has a pH value of 3.5 to 4.2. In any soil with a pH value below 4, free humic acid is sure to be present, whereas above pH 9 only its salts can exist. Between these two pH levels, both free humic acid and its salts can be counted upon to be present in varying proportion to each other. Acetic acid and oxalic acid as well as others may also be present in an acid soil, but they never play more than a minor role.

(3) The residual acidity of certain salts (see page 328)—whether naturally present or added to a soil—which result from the preferential ion absorption of plants. These may contribute to soil acidity when soil content of calcium carbonate is too low to counteract it.

(4) The mineral soil colloids—especially the clay colloids—which will have to be discussed in somewhat greater detail, because this particular phase of their influence has not been pointed out specifically in other parts of this book.

As was explained in Part III (page 158), such colloids originate when various silicate minerals—especially aluminum hydrosilicates, such as $H_4Al_2Si_2O_9$—decompose, resulting in the formation of clay. The establishment of a certain soil pH value depends to a large extent on the type of ions which are held adsorbed by these mineral colloids,[1] whereas a change in the pH value of a soil can become stable only when the acquired reaction—the ion charge—of these colloids is altered through base exchange.

Action of Hydrated Lime on Soil Colloids Saturated with Hydrogen. An acid clay, for instance, always holds a large amount of hydrogen (H^+) ions in adsorption, and it can readily be established experimentally that a pure hydrogen zeolite—an artificial mineral colloid which is saturated with H^+ ions—has in aqueous suspension (when soaked in water) a pH value of 2.9 to 3.1. When some of the H^+ (hydrogen) ions are replaced in base exchange by other cations, especially by Ca^{++} (calcium), the pH value rises proportionately. This process can be readily demonstrated by adding increasing amounts of hydrated lime, (calcium hydroxide) [$Ca(OH)_2$] to the hydrogen zeolite suspension, and the resulting reaction may be illustrated by the following equation:

$$\underset{\text{hydrogen zeolite}}{H_2Ze} + \underset{\text{calcium hydroxide}}{Ca(OH)_2} \rightleftharpoons \underset{\text{calcium zeolite}}{CaZe} + \underset{\text{water}}{2H_2O}$$

This means that the calcium ions are adsorbed by the colloids (zeolites) until all of the hydrogen ions have been replaced, which will result in a rise of the pH value to 9 or 9.5.

When calcium carbonate (limestone) is used instead, the replacement of hydrogen (H^+) by calcium (Ca^{++}) proceeds much more slowly, and complete saturation of the colloids with calcium is quite impossible because the much lower solubility of calcium carbonate results in a much lower concentration of Ca^{++} ions. The loss of valuable plant nutrients thus is avoided. Besides, this reaction (see page 175) results in the evolution of carbonic acid, which assists in stabilizing the pH value near the neutral point by causing the formation of bicarbonate. The danger of overliming, therefore, is much greater with hydrated lime, and the safer

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[1] Such as montmorillonite, beidellite, kaolinite, halloysite, hydrous mica, etc. In laboratory experiments, artificial zeolites (such as permutite) are employed.

as well as cheaper ground limestone may once more be recommended as preferable.

Recession of pH Value

It is a well-known fact that a higher pH level—established in an acid soil through liming—does not remain constant but drops back to a somewhat lower level after a certain time. At least part of the initial retrogression must be traced to the soil colloids (or zeolites), which do not immediately give up all of the H^+ ions they may hold adsorbed on their inner surfaces.

This can readily be observed when a suspension of acid soil in water, which through the addition of ground limestone has been raised to pH 7, is allowed to stand for several days under careful exclusion of the carbon dioxide of the air. Within 3 days the pH value will drop back from 7 to about 6.5, but longer standing—2 or 3 weeks—will produce no further change. When this experiment is repeated by again raising the pH value of the soil-water suspension to 7 through the addition of further amounts of ground limestone and by once more allowing it to stand for 3 days, the pH value this time will drop back to only about 6.8.

One Lime Application Insufficient for Permanent Improvement

That the pH adjustment of an acid soil by means of one lime application cannot be permanent should be rather obvious. The lime is, of course, incorporated only in the topmost 6 to 7 in., but the acid soil layer may be several feet in depth. Some of the calcium, therefore, is bound to leach away, and some of it will be absorbed by the plants growing in the soil. At the same time various organic and inorganic acids will continue to rise from the lower soil layers. As soon as there is no longer sufficient calcium carbonate present to neutralize these acids, the pH value of the soil will drop again. In consequence, an acid soil has to be limed regularly—at least every second year—and, even when after several years of heavy liming a more or less permanent pH level has been established, one must be continually on the watch for a gradual reassertion of the original acidity, checking the pH value at least once a year.

Rate of Raising the pH Value

With a highly organic acid soil a lime-requirement test may show that a very large amount of ground limestone—as much as 20 to 40 tons/acre or even more—would be needed to raise the pH value to 6.5. Even from a purely practical viewpoint, nobody would consider applying such huge amounts, but this would be very undesirable also as far as the plants and the soil itself are concerned. In general, one should not apply more than 5,000 to 6,000 lb—or with a highly organic soil as much as 10,000 lb —/acre in one move. It must be sharply warned against raising the pH level at any one time by more than 1 unit, or with a sandy soil by more than 2 units, of the pH scale. A gradual change is preferable to a larger move toward neutralization, because it is not only more economical but also safer. The micropopulation of the soil will thus get a better chance for gradual adjustment, and the transition to an altered balance will be smoother. Besides, the larger the amounts of added lime, the more difficult will it be to mix the lime evenly with the soil, and the greater will be the danger of temporary spot overliming.

Time Required to Raise pH Value

A highly organic acid soil may require an annual application of 5,000 to 10,000 lb of ground limestone/acre for many years before it even approaches a pH value near neutral. The choosing of suitable crop plants which are able to succeed on a more or less acid soil will have to do the rest. Since calcium, at the same time, is an important plant nutrient and is otherwise beneficial in various ways (see Chapter 21), and since organic soils are, by nature, frequently lacking in this element, the application of a fair amount of limestone will usually produce superior results, even when it cannot accomplish an appreciable rise in pH value.

Summary of Treatment of an Acid Soil

For the convenience of the practical farmer and gardener, the main points which must be observed in the treatment of an acid soil may once more be summarized.

(1) The first step must always be the determination of the pH value of the soil, since lime application need be considered only when the soil has a pH below 6.4 to 6.5. To apply lime to soil by guess can have serious and most undesirable consequences if the soil is not acid, and it is, therefore, very important to realize that by no means all organic soils, and most certainly not all heavy clay soils, are acid. Especially in horticultural literature one frequently finds the statement—without reference to pH value—that heavy clay soils can be improved by liming. This is very dangerous advice, because an alkaline calcareous clay—and such

clay soils are common—may be nearly ruined by a heavy lime application, especially when hydrated lime is used.

(2) The pH value of a soil, by itself, can give no clue as to the amount of ground limestone needed to reach a certain level. This depends largely upon the degree to which the soil is buffered (see page 171) as well as on the manner in which it is buffered, varying with every kind of soil. To attempt to draw conclusions from the appearance or the color of a soil is equally futile, since the presence or absence of the mineral colloids which exert such a decisive influence cannot be detected by merely looking at a soil or by feeling it.

(3) A pH determination cannot reveal whether a soil contains much or little calcium for plant nutrition, since calcium sulfate—even when present in fairly large amounts—has next to no effect on the pH value of an acid soil. The amount of available calcium present in a soil can be determined only by means of soil analysis.

(4) The amount of ground limestone per acre required to raise the pH value of an acid soil to a certain desired level can be determined only by means of special lime-requirement tests.

(5) In the liming of any soil it is never advisable to apply much over 5,000 lb—or at the very most 10,000 lb—of ground limestone/acre in one move. When the lime-requirement test shows that much more than this amount is needed to accomplish the desired change of pH value, the neutralization of the soil should be extended over several years. Even when it has been established by means of a lime-requirement test that it is possible to raise the pH of a certain soil from acid to neutral—for instance from pH 4.5 to 6.5—by one application of less than 5,000 lb of ground limestone/acre, it will be preferable to proceed in at least two steps extended over 2 or 3 years. A new lime-requirement test must be made before each lime application.

(6) The adjustment of the pH value of an acid soil by means of lime application must not be expected to be permanent, and many years of regular and heavy liming will often be required to reach a state of near permanency. Even this must be watched by means of annual pH determinations, since gradual reacidification is very likely when liming is discontinued for a number of years. What happens in each case depends upon the type of soil with which one is dealing.

(7) The time of year—fall, spring, or summer—at which liming is carried out is without significance if ground limestone is employed. In general, it is advisable to wait from 1 week to 10 days after an application of ground limestone before sowing or planting, in order to make sure that the pH value has become stable. No harm, though, is likely to result

if one sows or plants within 1 or 2 days after a medium heavy limestone application.

(8) When hydrated lime has been applied to a soil, it is definitely not safe to sow or plant immediately afterward, and it will take approximately 3 months before the pH value of the soil becomes reasonably stable. The reason for this is that the calcium hydroxide will at first produce a steep rise in pH value, which recedes again gradually as the hydroxide is converted into carbonate and bicarbonate.

46. THE IMPROVEMENT OF ALKALINE SOILS

Differences in Treatment Compared with Acid Soils

Alkaline soils with a pH value above 7.5 and up to pH 9 or even higher present a much more complex problem than the acid soils which have just been discussed. The reason is that in the acid range one is dealing merely with the hydrogen (H^+) ion which—aside from its influence on soil reaction—is not harmful in itself. In the alkaline range, on the other hand, there are a number of different salts which not only cause a high pH value but which, in high concentrations, interfere directly with normal plant nutrition, some of them even being actually toxic. With the latter type of soil, therefore, it is not sufficient to lower the pH value; measures for amelioration must include the removal—or at least the lowering of the concentration—of the objectionable salts.

Distinguishing Between Alkaline Soil Types

One of the most troublesome of all the salts which may be present is sodium, though upper soil layers can contain large amounts of sodium only in arid or semiarid regions. Where annual rainfall exceeds 15 to 20 in. and where natural drainage is satisfactory, sodium leaches away into the subsoil. The presence of sufficient amounts of calcium actually makes it impossible for a soil to retain large amounts of sodium when precipitation and drainage are favorable. Because of this relationship between calcium, sodium, and water, one can readily distinguish between the alkaline soils of more or less humid regions and the alkaline soils of arid or semiarid regions.

Alkaline Calcareous Clay Soils of Humid Regions

In northeastern North America as well as in other parts of the world with a similar more or less humid climate, alkalinity is confined almost entirely to clay soils or clay loams which may have a pH value from near neutral to 8.2 or 8.3. Occasionally, organic soils with a pH value near 8 are found also, but sandy soils with a pH value much above 7 are quite rare where rainfall is reasonably abundant, usually existing only in true limestone regions. In either case the alkalinity is caused almost entirely by an excess of calcium and magnesium carbonate, sodium playing such a minor role that it is of no significance. When, in a region with reasonably high annual rainfall, the analysis of a clay soil with a pH near 8 shows a high calcium content, one can safely assume that sodium is not a hindering factor, even without the rather complex sodium analysis.

Fertility. Soils of this type generally do not present much of a problem. In the first place, their alkalinity is not so high as to be a serious hindrance, and, in the second, they are frequently rather fertile—or at least potentially fertile—having a fairly good content of phosphorus and potassium. Only nitrogen—especially ammonium—content is often quite low, and this must be adjusted through application of suitable fertilizer.

It is frequently observed with such soils that—though their total potassium content is high (2 to 3 per cent—40,000 to 60,000 lb/acre), with available potassium oxide ranging from 200 to 300 lb/acre—potassium absorption by the plants is poor or inefficient. The same applies to phosphorus, though not quite to the same degree. In consequence, it is sometimes recommended that fertilizers high in phosphate and potassium be applied, and it has been demonstrated by field experiments that this treatment does result in a higher uptake of phosphate and potassium by the plants, as well as in a certain increase in yield.

Actually, this is not the answer to the problem, because this treatment does not go to the root of the trouble, and, instead of improving the soil, it tends to give permanence to its basically unbalanced and unfavorably alkaline condition. The potassium is not fixed by such a soil, as is claimed —it could not be extracted as available if it were fixed—but its uptake by the plants is interfered with by the large surplus of calcium. (See page 245.)

Use of Ammonium Fertilizer. Such soils frequently have a low content in ammonium, and, when soil analysis shows this to be the case, the application of an ammonium salt—such as ammonium sulfate or ammonium nitrate at the rate of 500 lb/acre—will produce a very distinct improvement. Because of the calcium present, the residual acidity of these ammonium salts is not likely to cause any appreciable lowering of the pH value (possibly none at all), but both potassium and phosphate as well as iron, manganese, and magnesium will become much more readily absorbable (not necessarily more available) through the combined action of the ammonium and the sulfate. (See page 246.) The improved balance between nitrogen, phosphorus, and potassium will render both phosphate and potassium more effective.

Gradual Lowering of the pH Value. When this treatment is continued year after year—under careful control by means of soil analysis—and when acid fertilizers are applied instead of neutral ones, the pH value of the soil will gradually be lowered, resulting in over-all improvement. Provided that the soil is satisfactorily drained and that rainfall or irrigation is sufficient, calcium then will actually be lost from the soil, and a more favorable balance will gradually establish itself. The application of farm manure or the plowing under of green manure will be very helpful also, because the evolving carbon dioxide will promote the formation of calcium bicarbonate, which readily leaches away. Supervision by means of analysis must never relax, and the treatment of the soil must be adjusted from year to year to meet changing conditions.

The Role of Sulfur. Another promising procedure with such a soil is the application of elemental sulfur (flower of sulfur) which, when the pH value is approximately 7.5, may be applied at the rate of 500 lb/acre. Near or above pH 8, as much as 1,000 lb/acre may be applied. It will take several months before the effect of the sulfur becomes apparent, but eventually this also will result in a gradual lowering of the pH value and, provided that drainage is satisfactory, in a loss of some of the objectionable calcium surplus. The effect of the sulfur must be observed closely by means of repeated pH determination as well as of calcium and sulfate analysis. One should never apply sulfur haphazardly, merely guessing at the results. Dispersion of the sulfur in the soil is very important also, and the more thoroughly it is mixed with the soil, the more satisfactory will be the results. That a sulfur application can have no influence on the plant nutrient balance of the soil—especially as far as nitrogen is concerned—and that the latter has to be adjusted separately, will need no emphasis.

Modification of Soil in Garden Practice. Under garden conditions, where only a small area is concerned, it is possible to modify a calcareous clay loam so profoundly that even azaleas or high-bush blueberries can be grown successfully. As must be expected, however, this requires patience and perseverance and cannot be accomplished in 1 day or even in 1 year, if the change is to persist. The procedure includes the incorporation of acid sawdust plus acid peat moss with acid fertilizer (see page 168)—especially ammonium sulfate—as well as annual mulching with sawdust mixed with ammonium sulfate. Good drainage and ample watering, so that a good part of the surplus calcium will gradually be leached away, are very important also. Merely to dig a hole in an alkaline clay and to fill it with an acid soil mixture, is of very little use, especially when such a hole cannot drain. Under such conditions the artificial acidity will be of very short duration, because the overwhelming mass of OH^- ions as well as Ca^{++} ions from the surrounding soil will infiltrate, and, when water can collect at the bottom of the hole and can rise from there, it will not be very long before the filled-in soil is as alkaline as the rest.

Dangers in the Use of Aluminum Sulfate. Aluminum sulfate, which is frequently recommended for soil acidification in gardens, is by no means as harmless as the general garden literature written for amateurs might lead one to presume. Actually, this is a rather dangerous substance, because the aluminum ion (Al^{+++}) itself and the various readily formed aluminates are rather toxic to plants. (See also page 233.) Besides, the addition of aluminum sulfate to a calcareous clay soil—though it is well capable of lowering the pH value rather quickly—will do nothing for the improvement of the physical condition of the soil, and its effect is not likely to last very long either. The above-recommended procedure employing sawdust, peat moss, and ammonium sulfate will work more slowly but is much safer and more satisfactory.

Alkaline Soils of Arid or Semiarid Regions

The second group of alkaline soils consists of those which can be taken into cultivation only with the help of artificial irrigation, and it includes some of the most difficult of all soils, as far as amelioration is concerned. No attempt will be made to cover this whole complex field, which is of a very special nature with numerous problems entirely peculiar to it, and which has been treated very ably by such experienced specialists as W. P. Kelley.[1] Only a general summary will be included here.

The main feature of these soils is that, because for long periods of their recent history they have received little rain—evaporation has exceeded precipitation—they may, though not necessarily do, contain various objectionable salts (especially sodium) which may have to be leached out before the soil can become arable. What makes their treatment so difficult is that they show a great variability in composition. This means that no one general manner of treatment can be expected to be successful under all circumstances so that no generally valid directions can be given.

Sulfur Effective Only in the Presence of Calcium. It is obvious, for instance, that the application of sulfur to a sodium-containing soil can produce a real improvement only when sufficient amounts of calcium are

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[1] Kelley, W. P., "Alkali Soils, Their Formation, Properties, and Reclamation," Reinhold, New York, 1951.

present at the same time. Without the calcium, which is needed to replace the sodium on the soil colloids so that the sodium can be leached out, one may succeed in lowering the pH value, but the sodium will remain and will be as objectionable as ever. In fact, some natural soils of this type have a slightly acid reaction—as low as pH 6—yet have a very high sodium content.

Limitations of Gypsum. Gypsum, on the other hand, which is frequently recommended for the amelioration of saline soils, can become effective only when the soil does not have a high calcium carbonate, a high sulfate, or a natural gypsum content. The latter is not infrequent with soils of this type, and thorough leaching alone then will usually be sufficient.

Magnesium also is sometimes present in excessively high amounts and will likewise have a limiting influence on plant growth. Since its chemical behavior is very similar to that of calcium, it is responsive to the same type of treatment suggested above (page 414) for the reduction of a high calcium surplus.

Leaching. For the successful leaching of a soil in order to remove salt, the physical condition of the soil, the nature of the subsoil, and the height of the water table are of vital importance. The subsoil frequently has an even higher salt content than the topsoil; the topsoil may, in fact, be in good fertile condition, lacking only water, while the undesirably high salt content is entirely confined to the lower soil layers. When such a soil is temporarily flooded for the purpose of providing an adequate water supply for a crop to be planted later, or even when it is merely irrigated without making sure of satisfactory drainage, the dissolved salts will gradually rise to the surface, and the soil is likely to become unfit for further cultivation after producing only a few good crops.

Drainage and Soil Permeability. Good drainage, therefore, is of vital importance in all efforts to render arid soils arable, even when irrigation only appears to be needed, and drainage must be provided by means of tiles or ditches wherever the subsoil conditions warrant it. Thus the leaching of a saline soil is feasible only when the soil is reasonably water permeable. In consequence, reclamation has always been most successful with saline sandy loams, whereas certain saline clay soils appear to be quite unreclaimable for the present.

Farmers working with arid or semiarid soil should make sure not only of their water rights but also of the drainage possibilities. In many instances the only practical line permitting successful drainage will have to run across a neighbor's field, and a cooperative arrangement with mutual give and take will then be the only possible solution.

Green Manure an Important Aid. It has been found that the most satisfactory initial step in the reclamation of saline soil, after preliminary leaching, is the establishment of a salt-resistant plant—Bermuda grass (*Cynodon dactylon*), Rhodes grass (*Chloris gayana*), rye grass (*Lolium perenne*) or others—which is later plowed under for green manure. This may be followed by alfalfa or sweet clover (*Melilotus alba*), which should likewise be plowed under.

Without doubt, it is foolhardy to attempt the reclamation of a saline soil, or even merely the irrigation of an arid soil, without thorough advance examination and analysis of the soil, including the subsoil. The history of arid soil irrigation recounts many dismal failures, sometimes on a very large scale. The investment in money or labor, or both, required to assure adequate irrigation of an arid soil is too great to risk failure, and it should never be considered without the expert advice and guidance of a trained specialist.[1]

Gardening on Saline Soil. For those who have to garden on a highly saline soil, a successful reclamation experiment, carried out by the Utah Light and Power Company and related by W. P. Kelley, may be cited. This tract of approximately 12 acres was located near Salt Lake City, only about 2 miles from the famous Great Salt Lake. It had formerly been flooded by the Great Salt Lake, and the soil was almost 100 per cent saturated with sodium. It contained a fair amount of calcium and magnesium, however, and—particularly important—it consisted of a rather readily drainable sandy loam.

The area was first tile drained and thereafter flooded with about 4 in. of water from a nearby well. After draining, it received a fairly heavy application of farm manure, and liberal irrigation was continued. Within 3 to 4 years after this treatment was started, the soil was improved to such an extent—merely through drainage, leaching, and one heavy application of manure—that fine lawns as well as many kinds of ornamental garden flowers could be established, and various types of vegetables gave excellent results.

The steps to be followed by the would-be successful gardener on a saline soil may be summarized as follows: First of all the soil should be

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[1] Where abundant rainfall occurs at a certain season, as in India, the rain water may be gathered in catch basins, and deep ditches for rain-water conservation should be dug all around the land to be reclaimed. When manure is unobtainable, weeds may be gathered for the production of an acid compost or may be allowed to rot in the rain water used for irrigation. The algae developing in such pits of rotting vegetation will assist in reducing alkalinity. With this simple procedure it has been possible to ameliorate even soil with a pH of 11—called "USAR" in India and previously considered as unreclaimable—to such an extent that a variety of crop plants, including rice, produced very satisfactory results. Kaul, K. N., "Conquest of USAR," Lucknow, India, National Botanic Gardens, 1958.

analyzed to find out whether it contains objectionably large amounts of sodium and, if so, what its calcium content is. In case the analysis shows a high sodium but a low calcium content, gypsum should be applied. A tile drainage then must be installed, and the soil thoroughly leached with water. Thereafter, manure should be applied and/or one may start by sowing Bermuda grass followed by alfalfa, both being plowed under as green manure. With continued irrigation and judicious applications of fertilizer, carefully controlled by analysis, the soil should continue to improve until it gives perfect satisfaction. This is the nearest one can come to giving general directions.

47. SOIL FERTILITY IN THE GARDEN

Danger of Overfeeding

In the home flower garden trouble frequently results simply from general overfeeding. Many gardening amateurs believe that, just as they feed their dog or their canary bird regularly, so they have to feed their plants, and the more generously they feed them, the greater will be their reward in flowers. There is justification for continual feeding where crop plants are concerned, which not only require a high level of soil fertility but are removed at maturity to make room for the next crop. What has been taken out of the soil must be replaced, or the soil will become progressively poorer. But perennial garden flowers which usually are set out in well-prepared fertile soil, remain in place for a number of years, and, therefore, require extremely little or no additional feeding. The soil itself will gradually mobilize further amounts of nutrients as some of those present in available form are absorbed by the plants.

Adaptation to a Low Level of Fertility

Many of our handsomest garden flowers—including most summer-flowering annuals—are by nature adapted to soils with a relatively low level of fertility. They respond to heavy feeding by becoming very lush, by flowering very little, and by falling prey to diseases as well as to frost injury. It is mainly for this reason that light applications of old compost—which represents a very mild but balanced feeding—give results so superior to commercial fertilizer on a flower border. Only when an old flower border is renovated and replanted may it be advantageous to apply limited amounts of commercial fertilizer, according to needs revealed by soil analysis.

The vegetable garden is a completely different proposition, and the raising of prize-winning vegetables, by means of maintaining the fertility of a limited area at optimum level, can give a great deal of pleasure.

Feeding of Hedges, Trees, and Grass

Moderate feeding every few years may be advantageous also with close-planted hedges as well as with shrubs and trees, where soil conditions warrant it. The accent, however, must be on the word "moderate." It is obvious that the feeding of a hedge—as long as this is not necessary in order to invigorate it—can only be undesirable, since it will, of course, result in strong growth which has to be removed by repeated clipping. The same applies to a lawn which—though it will not be satisfactory when allowed to starve—will only cause an unnecessary amount of labor by needing frequent cutting when it is fertilized too generously.

Alpine Plants

An extreme example of adaptation to a low soil fertility level is presented by our Alpine or rock-garden plants which, in consequence, suffer most severely when they are planted in overrich soil or are treated with fertilizer. Their mountain homes, on shingle and stone rubble or in rock crevices, force them to live on very little food, and they can actually be said to "thrive on starvation." The soils on which they grow are usually poor in nitrogen, because they contain little organic matter (this, of course, does not apply to mountain bog plants which are not considered here), and phosphorus and potassium become available only very gradually from the slowly weathering rocks. This starvation regime is one of the main reasons for the slow, compact growth of these plants—one of their greatest attractions—and those who wish to succeed with the cultivation of Alpines must heed these signs and must keep the plants on a very lean fare.

Because of the low level of fertility of the soils on which Alpine plants grow, water—moving, living water, not stagnant water—is of most particular importance to them. It is the water, together with the oxygen of the air (hydration and oxidation, see page 156), which causes the rock detritus to weather and to give up continuously the small amounts of mineral nutrients on which these frugal plants subsist. Provided that the soil composition is suitable and that drainage is satisfactory, frequent and thorough watering, therefore, serves, in this case, a particularly vital need.

Present evidence seems to indicate that, even at the generally low level of soil fertility to which certain plants are adapted, the most favorable balance between nitrogen, phosphorus, and potassium remains the same as at higher levels.

APPENDIX I

THE pH SCALE

The basic facts which have led to the development of the pH scale, as well as many of the details of its functioning, are frequently not fully understood, and, because of the importance of the problems involved, it appears desirable to give some further explanations. The question, for instance, is frequently asked: "Why does the pH scale begin at zero and end at 14?" The following example, which employs different concentrations of hydrochloric acid, will provide a readily understandable answer (though the authors of this book are well aware of the fact that the figures, as quoted, are not absolutely factual but represent approximate values).

Acid End of the pH Scale

Commercially available concentrated hydrochloric acid is a solution of hydrogen chloride gas (HCl) in water and contains 38 per cent hydrochloric acid (380 g/liter). When this acid is diluted with water, so that 1 liter contains 36 g of hydrochloric acid, the resulting solution will have a pH value of zero. The 36 g of hydrochloric acid represent 1 g H^+ ions and 35 g Cl^- ions, according to their atomic weight. When such a solution is progressively further diluted, always by 1/10, or, in other words, so that step by step every following solution contains only 1/10 as much hydrochloric acid as the preceding one, the following pH values will be obtained:

Amount of HCl/liter, g	H^+ ions/liter, g	pH value
36.0	1.0 $= 10^0$	0
3.6	0.1 $= 10^{-1}$	1
0.36	0.01 $= 10^{-2}$	2
0.036	0.001 $= 10^{-3}$	3
0.0036	0.0001 $= 10^{-4}$	4
0.00036	0.00001 $= 10^{-5}$	5
0.000036	0.000001 $= 10^{-6}$	6
0.0000036	0.0000001 $= 10^{-7}$	7

Two questions now arise:

(1) Why is the pH value of a diluted solution of hydrochloric acid at pH 7 the same as that of chemically pure water which does not contain any acid?

(2) Why does the scale end at zero, and what happens when more than 36 g of hydrochloric acid are added to the solution?

Both of these questions are rather easy to answer, provided one is willing to accept facts proved by experience, without continuing to ask: "Why are the facts the way they are?" There is no simple answer to that. Actually, the whole pH scale has been obtained empirically, which means that it is based entirely on experiments and observation. Therefore, it cannot serve to give reasons but simply presents facts as they are.

Question 1. When the hydrochloric acid solution is diluted until pH 7 is obtained, the H^+ ions of the water will be entirely suppressed, because it must be assumed that at such a high dilution the 2 ions of hydrochloric acid (H^+ and Cl^-) will be completely dissociated. The H^+ ions of the solution, which are responsible for the reaction of pH 7, will then come only from the hydrochloric acid, whereas the H^+ ions of the water will be undissociated in water molecules. As the above table shows, the amount of H^+ in the solution with pH 7 is exactly the same as that in pure neutral water, viz., 0.0000001, or 10^{-7} g/liter. (See page 89.) When a smaller amount than 0.0000036 g of hydrochloric acid is incorporated in the solution, or, in other words, when the solution is still further diluted, the pH will still remain constant at 7, because in that case the H^+ ions of the water will again become dissociated and active in exactly the required amount to maintain the total of H^+ (from both hydrochloric acid and water) at 10^{-7}. (The explanation as to why this happens is highly technical and will not be included here.)

Question 2. When more than 36 g of hydrochloric acid are added to 1 liter of water, the result will be that the amount in excess of 36 g will remain undissociated, which means that no free H^+ ions of the excess amount will be present. Since an undissociated acid has no influence on the pH, the pH will remain constant, even when still further amounts of acid are added. Again, there is no simple explanation. We simply have to accept this as one of the many peculiarities of water, which, however, is proved beyond a doubt.

Alkaline End of the pH Scale

Having studied the acid end of the pH scale (from zero to pH 7), the same may now be done with the alkaline section, up to pH 14, where the scale ends, though what happens is entirely analogous to what has just been described.

When one adds to chemically pure water of pH 7, instead of hydrochloric acid, sodium hydroxide (caustic soda, or, chemically, NaOH), which is alkaline in reaction, it will be found that approximately 40 g of sodium hydroxide in 1 liter of pure water will produce a pH value of 14. When such a solution is progressively further diluted, in the same manner as was done with hydrochloric acid, so that step by step every following solution contains only 1/10 as much sodium hydroxide as the preceding one, the following pH values will be obtained:

Amount of NaOH/liter, g	H^+ ions/liter, g	pH value
40.0	0.00000000000001 = 10^{-14}	14
4.0	0.0000000000001 = 10^{-13}	13
0.4	0.000000000001 = 10^{-12}	12
0.04	0.00000000001 = 10^{-11}	11
0.004	0 0000000001 = 10^{-10}	10
0.0004	0.000000001 = 10^{-9}	9
0.00004	0.00000001 = 10^{-8}	8
0.000004	0.0000001 = 10^{-7}	7

In this instance we are starting with 14 and are working down to 7, whereas on the acid end of the scale we started with zero and worked up to 7. The reason is that in both instances only the H^+ ion concentration is being considered. Hydrochloric acid adds free H^+ ions, and therefore the highest hydrochloric acid concentration produced the lowest pH figure. Caustic soda (NaOH), on the other hand, adds free OH^- ions, and therefore the highest caustic soda concentration, which increases the OH^- ion concentration to the maximum, produces the highest pH figure. This can readily be done—one can add free OH^- ions and still consider only the amount of free H^+ ions—because the total dissociated amount of the 2 ions together remains always the same. If there is more of one, there is correspondingly less of the other.

At pH 7 the same thing happens as was described for the acid end of the scale. It must be assumed that, at such a high dilution, the caustic soda is completely dissociated into Na^+ and OH^- ions, but the addition of the OH^- ions from caustic soda will make no difference in the reaction at pH 7, because an equivalent amount of OH^- ions from the water will become undissociated in water molecules. For the same reason, further dilution of the caustic soda solution will not result in pH readings below 7.

At pH 14 also, the same thing happens as was explained for pH zero. If more than 40 g of caustic soda/liter are added, the ions of this base will not dissociate further than up to the degree of dissociation reached at pH 14. Since undissociated caustic soda has no influence on the reaction of the solution, the pH will remain constant at 14, no matter how much more caustic soda is added.

For practical purposes one actually need keep no more in mind of all these explanations than the fact that at pH 7 an equilibrium exists between the 2 ions of water, H^+ and OH^-, which then are present, dissociated, in equal amounts. This equilibrium cannot be disturbed in either direction—to the acid or to the alkaline side—by further dilution with water.

As indicated previously, the above explanations of the pH scale are somewhat simplified. For those who wish to penetrate deeper into this interesting subject, a few additional scientific facts may be given.

Mathematical Calculations Supplying Further Information

By means of theoretical calculations based on fundamental laws of physics (the law of mass action), it was possible to prove that an equilibrium exists between the amounts of dissociated and undissociated water. Through extensive experiments it was further possible to establish the fact that the mathematical product of the concentration of dissociated hydrogen ions and the concentration of the dissociated hydroxyl ions in a solution $H^+ \times OH^-$, divided by the amount of undissociated water present at any pH value $\frac{[H^+] \times [OH^-]}{[H_2O]}$ is a constant. The experimentally established value of this constant (at 22°C) is 0.00000000000001, or written more simply 10^{-14}. The high-placed figure $^{-14}$ is the negative logarithm and indicates that 1 has been divided 14 times by 10. When working with such negative logarithms (potentials), it is well to remember also that their multiplication is accomplished by adding them, e.g., $10^{-1} \times 10^{-5} = 10^{-6}$. Since never more than a very small fraction of the water is dissociated into ions, the amount of undissociated water present is always so incomparably larger than the mathematical product of the concentration of the 2 ions that the concentration of undissociated water may be considered as constant, without causing any noticeable error, and may, therefore, simply be disregarded. The above formula thus may be reduced to $(H^+) \times (OH^-)$, which means that the formula for chemically pure water may be written $10^{-7} (H^+) \times 10^{-7} (OH^-) = 10^{-14}$.

The constancy of the equilibrium prevails likewise when the H^+ ion concentration is increased, for instance to 10^{-4}, by adding an acid to the chemically pure water. According to the above-outlined principles, the concentration of free OH^- ions will then, by itself, decrease to 10^{-10}, because $10^{-4} \times 10^{-10}$ equals 10^{-14}. The pH of such a solution then is 4, and, because H^+ ions are present in larger amounts than OH^- ions, the solution is acid. It is of interest to reflect, at the same time, that at pH 4 the solution contains 1,000 times as many free H^+ ions as pure water does, because 10^{-4} is 1,000 times larger than 10^{-7}.

When the H^+ concentration is decreased, for instance to 10^{-8}, by adding a base (such as sodium hydroxide), the amount of free OH^- ions must be increased to 10^{-6}, because $10^{-8} \times 10^{-6}$ equals 10^{-14}. The pH of this solution will be 8, and, because of the preponderance of OH^- ions, it will be alkaline in reaction. Since 10^{-8} is only 1/10 of 10^{-7}, the solution contains only 1/10 of the amount of free H^+ ions of pure water.

It is evident from the above outline that the acidity of a solution increases very rapidly with falling pH. pH 6 is 10 times, pH 5 is 100 times, and pH 4 is 1,000 times as acid as pure water at pH 7. The same applies, of course, on the alkaline side of the scale. This rapid increase has considerable significance, and it will now be understandable why it is undesirable to attempt changing the pH of a soil by more than ½ or at most 1 unit of the scale at a time.

APPENDIX II

COMPUTATION OF THE VALUE OF THE PROPORTIONALITY CONSTANT (c)

For those who are familiar with differential calculus, some details may be given here on the manner in which Mitscherlich's law of the diminishing yield increment is employed in mathematical computations.

For this purpose it is necessary first of all to designate the various basic factors which have to be entered in the equation, by letter symbols, as follows:

The maximal yield of a plant growing in an ideally fertile soil is designated by A.

The proportionality constant is c.

The amount of a growth factor present in the soil is x.

The amount of yield actually obtained with this amount of nutrient is y.

The law of diminishing yield increment can then be expressed by the following general equation $\frac{dy}{dx} = (A - y)c$.

The symbol dx represents the increase of a growth factor which produces a corresponding increase of yield dy, and $\frac{dy}{dx}$ is the differential quotient expressing the variation of the yield y produced by the variation of the amount of growth factor x. The assumption is that both y and x may represent any ever-so-small value, corresponding to the very short interval of the momentary law (see page 345), which latter is in effect at the moment the soil sample is gathered for analysis.

Integration and transformation of the general equation produce $\log (A - y) = \log A - cx$.

When, in this equation, the symbols are replaced by the respective figures, it becomes possible to compute the crop yield to be expected from the amount of a nutrient determined as present through soil analysis. This computation may be simplified by expressing the nutrient amount in Baule units, in which case the yield is obtained as a percentage of the maximal yield which any plant produces when growing in ideally fertile soil, the maximal yield A being 100 per cent.

For instance, when a soil contains 2.55 Baules of phosphorus (as P) (approximately 50/lb/acre), the following figures can be inserted in the above equation

$$\begin{aligned}
\log (100 - y) &= \log 100 - 0.301 \times 2.55 \\
\log (100 - y) &= 2 - 0.301 \times 2.55 \\
\log (100 - y) &= 1.23245 \\
y &= 82.92 \text{ per cent}
\end{aligned}$$

This means that, provided the other growth factors are present in optimal amounts, the presence of 50 lb/acre of phosphorus (as P) can be expected to produce 82.92

per cent of the maximal yield. The values given in Table 34.2, page 360, were computed in this manner.

It still remains to explain how the value of 0.301 for the proportionality constant c, as used in the above equation, was obtained. Since, according to the definition given on page 359, 1 Baule of any nutrient produces 50 per cent of the maximal yield A, the following values can be inserted in the above equation for the computation of c

maximal yield A = 100 per cent
yield y produced by 1 Baule = 50 per cent
quantity of nutrient = 1 Baule

The equation then reads

$$\begin{aligned} \log (100 - 50) &= \log 100 - c \times 1 \\ \log 50 &= \log 100 - c \\ 1.69897 &= 2 - c \\ c &= 2 - 1.69897 \\ c &= 0.301 \end{aligned}$$

This shows at the same time that when Baule units are employed in the calculation, the proportionality constant c always has the same value for all nutrients. On the other hand, it must be pointed out that when one figures with quintals per hectare or pounds per acre, the value of the proportionality constant differs with each nutrient, as shown in Table II.A.

TABLE II.A. COMPUTATION OF THE PROPORTIONALITY CONSTANT IN BAULE UNITS

	Proportionality constant computed for		
Growth factor	Quintals per hectare	pounds per acre	Baules
Nitrogen	0.122	0.0013	0.301
Phosphorus	0.60	0.00670	0.301
Potassium	0.33	0.00366	0.301

GLOSSARY

Acids. Combinations of hydrogen (H^+) ions with various anions under the exclusion of the hydroxyl anion (OH^-). Strong acids are almost completely dissociated into their ions at a pH range from 0 to 7. Weak acids are never more than partly dissociated, no matter how far they are diluted.

Acid soil. In the pH range below 6.5.

Aerobic. Requiring free gaseous oxygen.

Aggregation. From the Latin *aggregare*—to bring together. Referring, in soil, to the clumping together of small particles to form soil crumbs.

Alkaline soil. In the pH range above 7.2.

Alluvial. From the Latin *alluere*—to wash onto. Alluvial soil has been deposited by water.

Amorphous. Shapeless.

Anaerobic. The opposite of aerobic.

Analysis. Referring to the separation of a substance or a material into its component parts so that the latter can be examined and identified.

Anhydrous. Free of water.

Anion. A negatively charged ion, called *anion* because it is attracted to the positive electric pole, the anode.

Antibiotic. From the Greek words *anti*—against, and *bios*—life, because it suppresses life.

Aqueous solution. Solution in water.

Asymptote. A line which gradually approaches a curve closer and closer without ever actually touching it, which would make it a tangent.

Auxins. Substances promoting or influencing growth.

Bases (or alkalies). Combinations of the hydroxyl (OH^-) ion with various cations under exclusion of the hydrogen (H^+) cation.

Buffer and buffering. Refers, in soil terminology, to a solution or suspension which has the ability to offer resistance to a change in pH value. It thus acts as a buffer or "shock absorber."

Capillarity. From the Latin *capillus*—hair. Refers to the action of liquids which, in hair-fine tubes, are able to rise against gravity.

Carbohydrates. Compounds containing the elements carbon, hydrogen, and oxygen.

Carbonates. Salts of carbonic acid (H_2CO_3) such as calcium carbonate ($CaCO_3$).

Carbonation. A chemical process in which the molecule of carbon dioxide (CO_2), or the CO_3 ion of carbonic acid, enters into combination with one of the products of hydrolysis.

Catalyst. From the Greek *katalyein*—to dissolve. The term refers to substances which are able to hasten or to initiate chemical changes in other substances while they themselves remain unchanged.

Cation. A positively charged ion, called *cation* because it is attracted to the negative electric pole, the cathode.

Chlorophyll. From the Greek *chloros*—yellowish-green, and *phyllon*—leaf. The term applies to the green coloring matter of plant leaves and stems.

Chlorosis. Meaning a yellowish condition.

Chromosome. Meaning color bodies, because they stain brilliantly with certain dyes. The term refers to the minute bodies in the cells of plants which are the bearers of groups of hereditary characteristics.

Cohesion. Sticking together.

Colloid, colloidal. From the Greek *kolla*—glue, and *idos*—similar, meaning gluelike.

Deflocculation. Destruction of aggregation.

Diffusion. From the Latin *diffundere*—to pour. The term refers to the spreading of a solution through a liquid which serves as its solvent.

Dissociate. To split apart into its components.

Divalent. From the Latin *dis*—twice or two, and *valere*—to be worth.

Double decomposition. A chemical process in which a dissolved substance acts on another dissolved substance, resulting in the production of a new substance which is insoluble in water and is precipitated. The soil colloids are not involved.

Dynamic. From the Greek *dynamis*—power. Relating to physical force, energy, or power.

Elutriate. From the Latin *eluere*—to wash out.

Enzyme. From the Greek *enzymos*—leavened, because of the ability of certain enzymes to cause fermentation.

Exfoliation. Scaling off.

Feldspar. From the German *feld*—field, and *spat* or *spar*—designating various lustrous, easily cleavable, nonmetallic minerals.

Genes. The smallest still identifiable complexes of hereditary characteristics, composing the chromosomes.

Granulation. From the Latin *granulum*—small grain.

Growth factor. Any of the decisive factors which govern plant growth.

Hydrate and hydroxide. All compounds which contain molecules of water are hydrates; those which contain groups of hydroxyl (OH^-) ions are termed hydroxides.

Hydration. A chemical process in which undissociated molecules of water (H_2O) join the molecules of other compounds, forming new substances.

Hydrolysis. From the Greek *hydor*—water, and *lysis*—breaking up. Refers to a chemical process in which the water dissociates beyond its normal rate, while either one of its two ions (H^+ or OH^-) enters into new combinations with other anions or cations.

Hygroscopical. From the word *hygros*—moist, and *skopein*—to see, referring to an instrument, the hygroscope, with which such moisture can be measured.

Igneous. From the Latin *ignis*—fire. Resulting from the action of fire, such as volcanic action.

Ion. The Greek *ion*—going. Applied to the minute, electrically charged particles which move about under the compulsion to establish electrical equilibrium.

Leguminous. Relating to plants belonging to the pea family, Leguminosae.

Lignin. From the Latin *lignum*—wood. The substance lignin derives from the woody skeleton of plants.

Lithosphere. The crust of the earth, including the soil as far as it has not been deposited on top by wind or water. The humus layer is not included either.

Membrane. From the Latin *membrana*—skin.

Metabolism. From the Greek *meta*—beyond, and *ballein*—to throw (metabole—change), referring to the continuous chemical changes accompanying all life processes. It comprises two phases: anabolism, which is constructive; and catabolism, which is destructive. In anabolism, energy is required to accomplish the work involved; in catabolism, complex compounds are broken down into simpler ones in order to obtain the energy thus freed. The waste products are excreted. A proper balance between the two phases of metabolism spells health for any living organism, including man.

Metamorphic. From the Greek *metamorphustai*—to be transformed. Here applied to rocks which have been transformed through heat and pressure.

Molecule. The Latin *molecula* is the diminutive of *moles*—mass. The term is used to designate the smallest unit into which a substance can be divided while still retaining its composition and properties.

Morphological. Pertaining to the anatomy or structure of plant or animal bodies.

Mulch. An insulating layer of loose material, applied over the surface of the soil.

Mutant. Meaning changeling, from the Latin *mutare*—to change.

Mycelia. The threadlike vegetative growth of fungi.

Mycorhiza. From the Greek *mykes*—fungus, and *rhiza*—root, meaning root fungus and referring to certain types of fungi which live on the roots of certain plants and are always found associated with them. A sort of partnership, called *symbiosis* (living together), exists between certain higher and lower plants which is beneficial to both.

Neutral soil. In the pH range from 6.5 to 7.2.

Nodule. A small knot.

Omnivorous. Eating anything.

Osmosis. From the Greek *osmos*—impulse, referring to the impulse which causes a liquid to diffuse through a permeable membrane.

Oxidation. Applies to the chemical processes which result in the inclusion of oxygen in the molecule of a compound.

Permeable. From the Latin *permeare*—to pass through, meaning passable.

Photosynthesis. From the Greek *photos*—light, and *synthesis*—putting together, referring to the combining of elements into compounds by utilizing the energy of light.

Physiology, physiological. Dealing with or relating to the properties and functions of living organisms. From the Greek *physis*—nature.

Proteins. From the Greek *proteios*—primary, holding first place, because of their importance. Complex compounds of carbon, hydrogen, oxygen, nitrogen, and other elements.

Protozoa. From the Greek *protos*—first or primitive, and *zoa*—animal.

Reduction. Applied to a chemical process in which oxygen is removed from a compound.

Residual. Referring to the delayed action of what remains behind.

Respiration. A gaseous interchange, commonly called *breathing,* in which carbon dioxide, the main oxidation product, is discharged. Respiration in plants, contrary to photosynthesis, does not require light and goes on in all cells, whether they contain chlorophyll or not.

Salts. Compounds resulting from the combination of cations and anions under the exclusion of both H^+ and OH^- ions.

Saprophyte. From the Greek *sapros*—rotten, and *phyton*—plant. Applied to plants which live on decaying organic matter.

Sediment, sedimentary. From the Latin *sedere*—to settle. Having settled from water.

Sterile. Free of microorganisms.

Symbiosis. The intimate living together of two organisms in such a manner that both benefit.

Synthesis, synthesize. Putting together, such as the combining of elements to form a compound.

Topography. From the Greek *topos*—place, and *graphia*—description, referring to the surface features of a region or area.

Unicellular bodies. Consisting of only one cell.

Volatilization. From the Latin *volare*—to fly, meaning to change into vapor or gas.

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