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# SOIL CHEMISTRY

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by

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With a Foreword by

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## FOREWORD

By

A. G. POLLARD

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To write a good text-book in a foreign language for foreign readers is a task requiring not only much courage and close acquaintance with the subject matter, but also an intimate knowledge of the attitude of mind and thought of the prospective readers. That Dr. Shawarbi possesses these attributes is evidenced by the results of his labours—the present text-book.

His training and experience in two Universities of this country and his first-hand knowledge of the organisation and activities of many research stations and agricultural departments here provide much of the background and subject matter of the book. Egyptian agriculture and its problems, so well known to the author, add further information and a refreshing breadth of view to many aspects of the work.

For the student of soil science the text-book should provide a valuable source of information, instruction and reference. At the same time, in his writing Dr. Shawarbi has combined simplicity with technical matter, and those interested primarily in other branches of agricultural science, without being specialists in soil chemistry, will find in the book much easy and profitable reading.

A. G. POLLARD.

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## AUTHOR'S PREFACE

SOIL problems have proved extraordinarily complex and their solution requires combined investigation by a team of scientists, including chemists, physicists, geologists and the various micro-biologists. It can however be claimed that the contribution of chemistry has been at least as great as that of any other science.

To-day the subject of soils has, therefore, assumed such immense proportions that its contemplation is bewildering, and one cannot hope to do more than learn the outlines of this subject of soils and give closer attention to some part of it. Hence we are going to confine ourselves in this book to soil chemistry.

The chemistry of the soil involves many and very different chemical compounds. The most important group is composed of the compounds of the element silicon, which make up more than 75 per cent. of the various soil layers. The remains of living organisms usually contribute from 1 to 10 per cent. of the weight of the upper few inches of surface soil. The silicon compounds and the carbon compounds, associated with life processes, are the most numerous and the most complex of the compounds found in nature. It is in the soil that inorganic substances are transformed into living organisms, and dead organic matter also changes back into inorganic compounds. The soil is the cradle and burial place of all life. In volume and quantity the soil, or broadly speaking, the pedosphere is relatively insignificant when compared with the other spheres of the earth, but it is the source of all living existence. Soils are thus intermediate between the dead and the living world, being the prime source and carrier of all life.

This goes to show, as will be seen from the following chapters, that the chemistry of soils is far from being simple and straightforward. Soil chemistry is in fact very complicated and in spite of the big advances made during the last thirty years, a great deal of the fundamental chemistry of the soil is still obscure. It must be admitted, however, that the state of our knowledge of general chemistry is a limiting factor to the development of soil chemistry.

Almost every new development in physical chemistry seems to throw fresh light upon soil problems. As knowledge increases in any science relationships that look complex can often be reduced to fairly simple laws. Studies of colloids, base exchange and soil reaction are merely three examples of present-day research in soil chemistry which will clarify so many of the obscure problems of this subject. Consequently practical applications that are of value in crop production will naturally follow.

It should be mentioned that much of the failure in applying chemistry to soil problems has been due to the elementary mistake of confusing soil material with soil as an individual in the field, of confusing the laboratory specimen with the natural body, the actual medium in which plants grow.

It has not been possible in this book to do more than to sketch the directions in which chemistry has been applied to the study of the soil. Many important aspects of soil chemistry have of necessity been omitted ; in particular the chemical analysis of soils requires separate treatment. It is hoped that some indication has been given both of the wide scope of the subject and the complexity of the problems involved. The book is written, however, in such a way as to discuss the various topics of the subject from first principles and follow them up until they go deeply into the problem. Thus it is sincerely hoped that this book will be of great help not only to advanced students but also to beginners, farmers, and workers in other fields of science such as geology, ecology, geography and plant physiology.

My cordial thanks are due to the authors of many books and papers mentioned in the bibliography, especially to those who kindly allowed me to make use of tables and diagrams from their publications. I wish also to express my great indebtedness to Sir John Russell, Prof. G. W. Robinson, F.R.S. and Mr. A. G. Pollard for their help and inspiration. The latter has been kind enough to undertake the laborious task of editing the book, and in collaboration with Dr. A. H. Cornfield, of checking the proofs.

M. Y. S.

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CHAPTER I

*Historical Background*

DURING the course of human history, men have interested themselves deeply in the problems of agriculture, and slowly there has been built up a certain body of knowledge for dealing with them. An important part of this knowledge has been gained by direct observation and experience, but in spite of the fact that agriculture was practised from the earliest times it remained purely an art, though an art which attained a great success in comparatively recent days. Developments of chemistry, physics, biology and other branches of natural science have begun to throw light upon many of the practices of agriculture which had been arrived at by the laborious methods of trial and experience.

Chemistry was the first pure science to come to the aid of agriculture. Agricultural chemistry, which was up to the middle of the last century mainly soil chemistry, could not exist until pure chemistry had developed; so we find that the subject was in a very hazy and unsatisfactory condition until the writings of Robert Boyle (1660) and Joseph Black (1755), the discoveries of Joseph Priestly (1774) and Henry Cavendish (1784), and the systematic arrangements of Lavoisier (1789) and John Dalton (1818) laid the foundations of modern chemical theory.

One of the first questions which suggests itself in connection with our subject is—of what materials are plants made and from where do they obtain these materials?

The earlier investigators sought for a "principle" of vegetation to account for the phenomena of soil fertility and plant growth. The great Francis Bacon, Lord Verulam (1627) believed that water formed the "principle nourishment" of plants, the purpose of the soil being to keep them upright and protect them from excessive cold or heat, but he also considered that each plant drew a particular juice from the soil for its sustenance, thereby impoverishing the soil for that particular plant and similar ones, but not necessarily for other plants. Van Helmont regarded water as the sole nutrient for

plants. Somewhat later Glauber believed that saltpetre (nitre) was the "principle" of plant life. He used some of it as fertiliser with very good results.

An entirely new method was adopted by John Woodward at the end of the seventeenth century. Starting with Van Helmont's experiment, and apparently not knowing about the work on saltpetre, John Woodward grew a plant, spearmint, in water and showed that something more than water was concerned. River Thames water was a better food than rain water, while Hyde Park conduit water was better still, and water that had been shaken up with garden soil was best of all. This, he said, showed that "terrestrial matter" and not water was the food of plants. This method has been much developed and is now widely used in botanical laboratories under the name "water culture".

In his celebrated textbook of chemistry, Boerhaave (1727) taught that plants absorb the juices of the earth and then work them up into food. The raw material, the "prime radical juice of vegetables, is a compound from all the three kingdoms, viz. fossil bodies and putrified parts of animals and vegetables."

Although for many years no such outstanding work as that of Glauber and Woodward was published, advances were being made in agricultural practice. One of the most important was the introduction of the drill and the horse hoe by Jethro Tull (1731). He insisted on the vital importance of getting the soil into a fine crumbly state for plant growth. Tull was more than an inventor, he discussed in most picturesque language the sources of fertility in the soil. Tull's views as to the food of plants were peculiar, and the arguments he employed were ingenious and had an apparently strong logical weight. He criticised Van Helmont's theory as to water being the food of plants and dismissed the hypothesis that air could form any part of a ponderable body. "The mouths or 'lacteals' of the roots take in their pabulum (being fine particles of earth) from the superficies of the pores or cavities wherein the roots are included." He regarded these fine particles as so small that they adhered to the larger particles of soil and can only be removed by the roots with the "assistance of water which helps to loosen them." The main object of agriculture was, according to his views, to increase the "pasture" of plants by increasing the "internal superficies". This was brought about by sub-division of the soil by tillage operations. All plants lived on these particles, i.e. on the same kind of food.

The Edinburgh Society, established in 1755 for the improvement of arts and manufactures, induced Francis Home (1757) "to try how far chemistry will go in settling the principles of agriculture." The whole art of agriculture, he said, centred on one point; the nourishment of plants. Investigation of fertile soils showed that they contain oil, which was therefore thought to be the food of plants. But when a soil had been exhausted by cropping, it recovers its fertility on exposure to air. Thus air seemed to supply another food.

This work was a great advance on anything that had gone before, not only because it recognised that plant nutrition depended on several factors, but also because it indicated so clearly that there were methods to be followed in studying the problem, i.e., pot cultures and analysis.

In 1761, Wallerius, Professor of Chemistry at Upsala, after analysing plants to discover the materials on which they lived, concluded that humus, being homogeneous, was the source of their food—the nutritiva—while the other soil constituents were instrumentalia. The latter made the proper food mixture, dissolving and attenuating the nutritiva, and facilitated the entry into the plant root. Thus chalk and probably salts help in dissolving the "fatness" of the humus. Clay helped to retain the "fatness" and prevent it being washed away by rain; sand kept the soil open and pervious to air. Manures were thus divided, as by Wallerius, into two classes; those that afford plant food and those that have an indirect effect.

In 1795 the Earl of Dundonald published a book in English under the title *A Treatise showing the intimate connection that subsists between Agriculture and Chemistry addressed to the Cultivators of the soil, to the proprietors of Fens and Mosses in Great Britain and Ireland and to the Proprietors of West Indian Estates*. However, the amount of new light which the book threw on this subject was certainly not proportional to the length of the title.

Little advance in our knowledge of the source of plant food was possible until the chemical nature of the atmosphere had been investigated, i.e. until the discoveries of Priestly, Scheele, Cavendish and Black led to some clearer knowledge of the properties of oxygen, nitrogen, carbon dioxide and other gases.

During the first thirty years or so of the 19th century little advance was made, though the delivery of a series of lectures on the subject, from 1802 to 1812, by Sir Humphrey Davy, and their publication in book form in 1831, did much to emphasise the

importance of applying chemical principles to agricultural problems.

A new method of approach was meanwhile being developed. Chemists were discovering how to analyse plants and soils so as to find out the substances present in them. It was assumed that if a substance occurred in the plant it must be serving some useful purpose and therefore must be supplied in the plant food. Later work showed that this was not quite correct, nevertheless the idea served a useful purpose. The new chemical methods were used to great advantage by the French agriculturist Boussingault, who was the first to set up a laboratory on the farm and to make true scientific field experiments. Boussingault can be regarded as the founder of agricultural science. On his farm at Bechelbronn in Alsace he carried out a magnificent series of experiments in all branches of agriculture. In one of these he weighed and analysed all five crops of a rotation, in order to discover what the plants had taken up ; he analysed also the farmyard manure to find what it had supplied, and so by difference discovered the amounts of substances that had come from the soil and the air. This showed that the plant consisted very largely of carbon and oxygen, of which the manure could have supplied only a part, and as the soil was in approximately the same state at the end of the rotation as at the beginning it was assumed that the elements had not come from the soil. Later work confirmed this fact. Both carbon and oxygen came from the air, and as these form some 90 per cent. of the dry weight of the plant we now have the true explanation of Van Helmont's result ; it was the air and not the water that gave the increase. ✓

In 1840 Von Liebig's famous report to the British Association upon the state of organic chemistry was published as *Chemistry in its Application to Agriculture and Physiology*.

Liebig's book was meant to attract attention to the subject, and it did ; it rapidly went through several editions, and as time went on Liebig developed his thesis, and gave it a quantitative form : " The crops on a field diminish or increase in exact proportion to the diminution or increase of the mineral substances conveyed to it in manure." He further adds what afterwards became known as the Law of the Minimum " by the deficiency or absence of one necessary constituent, all the others being present, the soil is rendered barren for all those crops to the life of which that one constituent is indispensable."

These and other practical deductions were seized upon and shown

to be erroneous by Lawes and Gilbert (1847) who had for some years been conducting vegetation experiments. Lawes did not discuss the theory as such, but tested the deductions Liebig himself drew up, and found them wrong. Further trouble was in store for Liebig; his patent manure when tried in practice had failed.

Yet the failure of the patent manure was not entirely the fault of the theory, but only afforded further proof of the numerous pitfalls of the subject. The manure was sound in that it contained potassium compounds and phosphates (it ought, of course, to have contained nitrogen compounds), but it was unfortunately rendered insoluble by fusion with lime and calcium phosphate so that it should not too readily wash out in the drainage water. Not till Way had shown in 1850 that soil precipitated soluble salts of ammonium, potassium and some phosphates was the futility of the fusion with lime discovered, and Liebig (1851) saw the error he had made.

The reasonableness of Liebig's views and the power of his influence put an end to the alchemists' theories of plant growth. His theory, however, received a serious blow with the discovery of bacteria, especially of those responsible for the fixation of atmospheric nitrogen, but it recovered from its first blow and even dominated much of the agricultural thinking in Western Europe until recent years.

Although the theory was a great advance at the time, it probably did more to retard the development of soil chemistry during the early part of this century than any other factor. In accordance with such a concept, the soil was considered a more or less static storage bin of plant nutrients. Thus the theory singularly failed to recognise the dynamic nature of the relationship between the soil and the plant.

Early this century the dynamic and complex nature of the soil was recognized. Various branches of pure science were applied to the elucidation of the nature of the soil. This gave rise to the various branches of soil science, namely soil chemistry, soil physics, soil microbiology, soil genesis, soil fertility and soil technology. Books on soils dealt always with the subject as a whole, comprising two or more of the above-mentioned branches. The present writer has confined himself in this book to the chemistry of the soil. In so writing it is unavoidable to touch on the other branches of soil science.

## *The General Composition of the Soil*

A typical soil consists of :—

[a] **Gritty, crystalline particles of Quartz.** The angles of these crystals may be rounded, indicating transport by water, or sharp, indicating formation on the spot. Fragments of primary rock are also generally present. The source of these is indicated by mineralogical experiments.

[b] **Colloidal particles.** These furnish the soil with its plasticity, absorptive capacity for nutrient salts and  $H_2O$ , and may be either mineral colloids, organic colloids, or more usually both. The mineral colloids generally predominate except in peat and bog soils, in which organic colloids form the majority. The mineral colloids consist of silicates of iron and aluminium capable of forming gels. They occur in the clay fraction, the sub-division of which by centrifugal methods show that marked colloidal properties increase as the size of the particles decreases. These mineral colloids exhibit a *cohesive force* by acting as a cement to form aggregate particles. If an excess of colloids is present in the soil, then on drying, a hard mass, difficult to break up, results, e.g., in clays. Such clay soils can take up a large amount of water and retain it under drying conditions, due to the colloids present. On drying, a shrinkage in the volume of clay occurs, and cracking of the soil results. *Organic colloids* exhibit properties similar to those of the mineral colloids; they can absorb more water than do mineral colloids, their cementing effect is quite as great, and their shrinkage on drying is much greater.

[c] **Chalk.** Living processes in the soil tend to yield acid products. Some crops are sensitive to this acidity which is normally counteracted by the presence of chalk in the soil. The proportion of chalk present often determines the nature of the manurial treatment and the types of crops grown.

In addition, however, soil contains moisture, gases and living organisms. We may picture the soil as a three-phase system. The

solid phase is composed of the mineral matter and the organic matter. The liquid phase is in equilibrium both with the solid phase—the mineral and organic matter—and the gaseous phase—the soil air. But the equilibrium is continuously shifting owing to the variations in temperature and in water content, the drain of nutrients by plant roots, and the activities of micro-organisms. With these variations are associated corresponding changes in the composition of the gaseous phase—the soil air. It is obvious then, that the solid phase of the soil offers a better basis of study than the rapidly changing and dependent liquid and gaseous phases. Indeed, for many purposes, the study of the soil is synonymous with the study of soil mineral matter and soil organic matter in the dried laboratory samples. But, when it is necessary to link up the study of the soil with that of the growing plant, a more complete knowledge of the conditions in the soil solution and the soil air becomes essential.

#### THE MECHANICAL COMPOSITION OF THE SOIL

A general knowledge of the mechanical composition of the soil, i.e. the relative proportions of the different sized particles, is of the highest importance for the purpose of characterizing the soil and also because it affords an indication of its physical and chemical properties, more particularly in respect of its behaviour under cultivation.

The process whereby the mechanical composition of the soil is determined is called mechanical analysis.

A mechanical analysis is useful for :—

(a) Estimating the properties of the soil, e.g. a high-clay soil will show water retention and plasticity.

(b) Cultural purposes, e.g. manuring. Thus a stiff clay soil would require organic matter to make it more easily workable due to mutual flocculation. Chemical fertilisers would tend to be retained by clay soils over the rainy season. Sandy soils would require heavy dressings of organic manures, to provide humus, and thus hold water and nutrients.

(c) As a guide for crops as regards water and nutritive properties. Crops take up definite amounts of water and nutrients. Some are heavy mineral feeders and absorb the bulk of this at a particular stage of growth. Thus these requirements must be correlated with optimum feeding conditions.

## METHODS OF MECHANICAL ANALYSIS

The methods which have been adopted, and the ways in which the results of mechanical analysis have been expressed, have undergone rather rapid revision in recent years, and the literature still contains large numbers of mechanical analyses of soils made by methods now no longer used, and expressed in ways which have now been superseded. It will therefore be necessary not only to describe present methods, but briefly to consider the methods which preceded them. The following fractions are recognized by international agreement : (See Table 1.)

TABLE 1

<i>Diameter in mm.</i>	<i>Fraction</i>
Above 2 ... ..	Gravel
0.2-2 ... ..	Coarse sand
0.02-0.2 ... ..	Fine sand
0.002-0.02 ... ..	Silt
Less than 0.002 ... ..	Clay

While the coarser fractions consist mainly of original fragments—quartz, feldspars, micas, etc.—and are mainly inert, the clay is made up almost entirely of weathered products and is reactive. In the field the particles are bound together into aggregates known as soil “crumbs” the binding materials being clay and organic matter. After dispersion of the “crumbs” clay and silt are estimated by the use of Stokes' Law governing the rate of fall of particles in a liquid, viz. :

$$v = \frac{2gr^2(d_1 - d_2)}{9\eta} \quad \text{where } v = \text{velocity of fall}$$

$g$  = acceleration of gravity  
 $d_1$  = density of the particle  
 $d_2$  = density of the liquid  
 $\eta$  = viscosity of the liquid  
 $r$  = radius of the particle

i.e., the velocity of fall is proportional to the square of the diameter. There are, however, at least two facts which make the strict application of this equation to falling soil particles invalid : firstly, the soil particles are not clean-cut particles of rock material with a definite radius, but are coated with gelatinous material which gradually merges into the surrounding water ; secondly the particles are not spherical as shown from (Fig. 1).

It may be noted here that the clay fraction (by which is understood the portion of the mineral matter consisting of particles of less than 0.002 mm. diameter) is chemically reactive and affords interesting examples of the application of chemistry to the soil. It does not correspond to the "clay" of ceramic chemists who adopt a larger limit of size (0.01 mm.) but apply the name to a rather narrow group of minerals only.



*Fig. 1.* Very fine sand and silt as they appear under the microscope. The figure indicates clearly the great differences in the shapes of the various particles.

**Direct Methods of Mechanical Analysis.** The earlier methods were all "direct" methods in the sense that the various fractions were literally separated one from another and weighed.

**Elutriation Methods.** In elutriation methods the fractions were separated from one another by means of currents of water of different velocities. None of these methods is now in general use in soil laboratories. One form of apparatus designed by Nobel for this purpose is illustrated in Fig. 2. To carry out the determination about 1 oz. of soil is to be put into the smallest of the pear-shaped

vessels and water is run in from W. As the vessels are of different diameters the water flows through them at different rates, going most rapidly through the narrowest and most slowly through the widest, D. When it runs rapidly it carries away the fine and intermediate particles leaving only the coarsest : as it goes more and more slowly it deposits finer and finer particles. Hence after a time the soil put

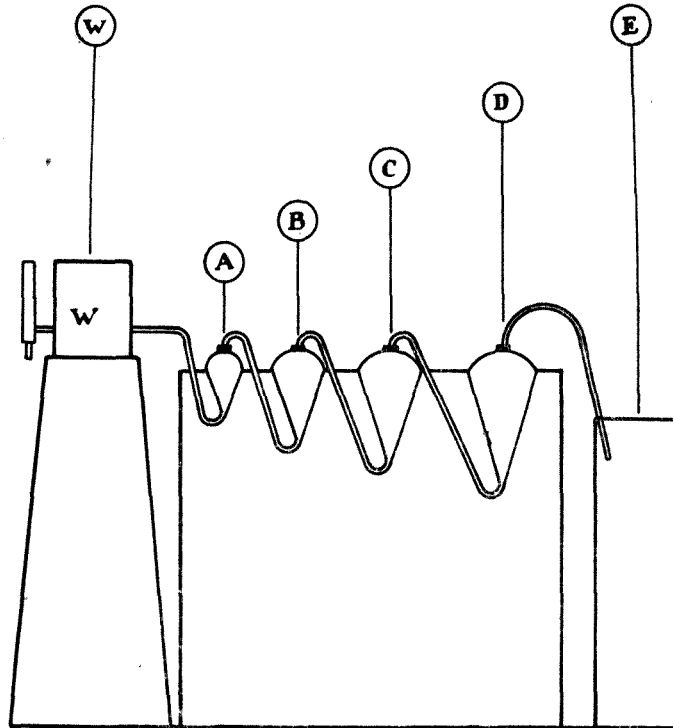


Fig. 2. Nobel's apparatus for mechanical analysis of soils.

into the apparatus has become sorted out into grades, the coarsest particles only remaining in the smallest vessel A, while the other portions of successively finer particles are distributed over the larger vessels B, C, and D, till finally the smallest particles of all are washed out into the large vessel E.

**Decantation Methods.** In decantation methods the suspended particles were allowed to settle through a column of water of prescribed height during a definite time until, as calculated from

Stokes' Law, the suspension contained only particles below the highest diameter or settling velocity of the smallest fraction. The suspension was then decanted off, the sediment resuspended and the whole operation repeated again and again until the whole of the smallest fraction had been removed by decantation. The next highest fraction was collected similarly, and so on until one fraction remained as a residue.

**Indirect Methods of Mechanical Analysis.** If a mixture of particles of different sizes and different velocities of fall is allowed to settle through a column of liquid, then at any given point in the suspension there will be a change with time in (*a*) density, (*b*) hydrostatic pressure, and (*c*) mechanical composition. A number of methods have been devised in which observations of one or other of these changes are made use of to calculate indirectly the mechanical composition of the original suspended material.

The method now in general use, which is perhaps the simplest and most satisfactory of them all, is based upon the work of G. W. Robinson. The primary consideration involved in this method can easily be seen in the following way. If three different suspensions be made up of particles of three different sizes, each suspension will begin to clear from the top downwards as the particles fall. At any given time there will be a greater depth of clear water in the suspension containing the larger particles which fall more rapidly than in the suspensions containing smaller particles. If now, the three groups of particles are mixed together in one suspension, the same sort of thing will happen, so that at any given time there will be three positions in the suspension, one denoting the top of the column of medium particles, and above that will be the top of the column of small and most slowly falling particles. By introducing a pipette into such a suspension of appropriate depths and after calculated times of standing, it is possible to draw off :—

- (*a*) a mixture of all three grades of particles ;
- (*b*) a mixture of the medium and the small particles ;
- (*c*) the small particles only (*see* Fig. 3).

This method is also called the "pipette method", "the depth concentration method" and the "A.E.A. method". The latter name arises from its official adoption by the Agricultural Education Association.

**Mechanical Composition as a Continuous Function of Particle-size.** On account of the obvious drawbacks to these

arbitrary size limits, considerable effort has been devoted to the perfecting of methods whereby the mechanical composition of soils can be expressed as a continuous function of particle-size. S. Oden first attempted this by means of an apparatus in which the mechanical analysis of a soil or clay is automatically recorded by measuring the accumulation of falling sediment on a balance pan. G. Wiegner also devised an apparatus in which the change in density of a column of sedimenting suspension can be continuously recorded.

**Dispersion of Soil Suspensions.** The validity of a mechanical analysis depends on the thoroughness with which the soil is resolved into its constituent particles by the dispersive treatment which pre-

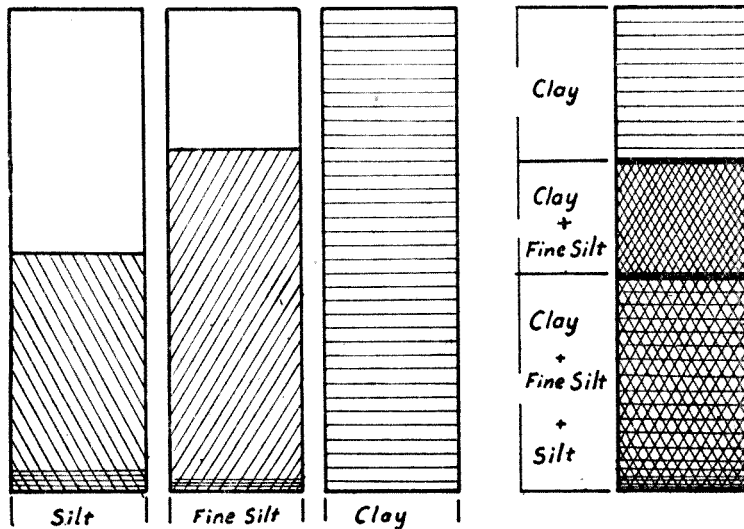


Fig. 3. Diagrammatic representation of the settlement of mixed particles.

cedes the actual mechanical analysis. For this reason a considerable amount of work has been directed towards discovering the most efficient method of preliminary treatment. The aim of this preliminary treatment is to break down compound aggregates and to bring the soil to its prime particle structure. Many of the earlier analyses were untrustworthy because complete dispersion was not effected, with the result that a proportion of the material analysed consisted of compound aggregates and not of ultimate particles.

The method of dispersion now adopted by the International Society of Soil Science, known as the International A-method,

consists in boiling with 6 per cent. hydrogen peroxide to destroy humus, treatment with 0.2 N-hydrochloric acid and washing to remove carbonates and bases combined with clay and humus, and final dispersion by shaking in 0.008 N-sodium hydroxide.

**Aggregate Analysis.** Attention is now largely focused on the aggregates themselves instead of only on the separate particles composing them. Various attempts have been made to find some concise expression of the structural character of a soil and state of aggregation of its particles. Some definitions of structure are expressed in terms of the proportion of prime particles below a specified diameter that are bound in aggregates above that same or some other specified diameter.

Several workers have investigated the possibilities of aggregate analysis but there is no final and ultimate definition of an aggregate. Some investigators are concerned to determine the size of aggregates as they exist in the field, although these are admittedly not permanent. At the other extreme there is the conception of what are virtually permanent aggregates, and intermediately the water stable aggregates may be considered. It is not many years ago that the problem of making mechanical analyses of soil, that is of determining the sizes of the *prime particles*, was beset with the difficulty of getting a complete disintegration of the aggregates and the independence of the prime particles, as above mentioned.

**Weathering of Soil Material.** The question now arises : Why are the particles so different in size ? An obvious answer is that the large particles are perpetually breaking up into little ones and that the silt represents a sort of half-way stage between gravel and clay. This, however, is not the whole explanation. The clay contains substances that are not in the sand, as is shown by the following experiment. Put into one test-tube 1 gm. of the sand and into another 1 gm. of the clay : add 20 c.c. of strong hydrochloric acid to each, plunge the test-tubes into a vessel of boiling water and leave for an hour. Hydrochloric acid is a potent solvent, and dissolves material that is not highly resistant. At the end of an hour the clay is seen to yield a markedly coloured solution while the sand only gives a slightly yellow solution : dilute and filter these and add ammonia to each until the liquid turns red litmus blue : the solution from the sand gives only a slight precipitate while that from the clay gives a much denser one. Thus we conclude that sand is much more resistant to the attack of acids than is clay. The same result is

obtained when the sand and the clay are exposed to the weathering agencies : the sand resists more than the clay and therefore is less completely broken down.

✓If the soil as a whole, including the fractions isolated in mechanical analysis, is examined closely, it is seen that the larger particles, down to about 2 mm. diameter, are mainly fragments of rock, whilst the particles from 2 mm. down to about 0.002 mm. diameter are fragments of rock-forming minerals such as quartz, feldspars, micas, hornblende, and the like. Below about 0.002 mm. diameter there is a marked change in the character of the particles. Rock-forming minerals such as quartz and feldspars disappear and their place is taken by minerals not ordinarily present in original rocks. This fraction, consisting of particles below 0.002 mm. in diameter, therefore, differs profoundly from the coarser material. ✕During recent years much work has been done on the constitution of the so-called clay fraction. It differs considerably in different soils, but certain common characters may be noted, and will now be briefly enumerated.

Clay differs very widely from sand in its properties. It is very sticky and belongs to the class of substances called "colloids." It is such a dominating substance that even a small quantity impresses its properties on a large bulk of silt or sand, and a soil containing 20 per cent. of clay easily becomes quite sticky and hard to cultivate.

Surface development has an important effect on solubility and chemical reactivity. The more a material is subdivided the greater will be the proportion of atoms or atomic groups at the surface and, therefore, capable of reacting chemically. But this greater chemical reactivity of the clay fraction is not due entirely to its enormous surface development. The clay fraction includes minerals formed from the decomposition products of minerals present in unweathered rocks. These minerals, e.g. kaolinite, beidellite, and montmorillonite, to name a few of those that have been recognized, are actually more reactive than the original minerals from which they have been derived. In addition to definitely recognized minerals such as those mentioned, there is also present in the clay fraction material that is chemically reactive, but apparently possessing a less definite chemical constitution, and not even finely crystalline. The clay fraction of certain soils may also contain free hydrated ferric oxides which confer on it a reddish or yellowish colour. Hydrated alumina may also be present.

Much remains to be discovered about the nature of the constituents present in the clay fraction. One of the tasks awaiting soil chemists is the survey of the clay fraction of different types of soil. It is certain that there are important differences between soils in this respect, both in the actual constituents present and also in their relative proportions.

Thus it is evident that the representative mineral soil is a mixture of particles differing in size, in chemical composition, in mineralogical nature, and in physical and chemical reactive capacity. The particular group of particles that dominate an individual soil as well as the proportionate amounts of the others present determine the characteristics of that soil and have much to do with successful crop production.

**The Organic Matter of the Soil.** Organic matter is an essential constituent of all normally productive soils under field conditions. It is necessary for most of the soil organisms and is a natural source of nitrogen in the soil for higher plants.

Soil organic matter is derived mainly from plant residues. There is also a certain contribution from animal remains and excreta notably in the case of cultivated soils. Under forest vegetation the principal source of the soil organic matter is leaf fall.

Organic matter may well be considered as fuel for bacterial fires in the soil which operates as a factory producing plant nutrients. The organic matter is burned to carbon dioxide, ash, and other residues. This provides carbonic acid in the soil water, and the solvent effect of this acidified water on calcium, potassium, magnesium, phosphates, and other minerals in rock form is many hundreds of times greater than that of rain water. At the same time the complex constituents of the organic matter are simplified, and nitrogen in the ammoniacal form is converted into the nitrate form. This, very briefly, is the complicated process of decomposition, from which carbon dioxide results as the major simplified end-product, together with a lot of others in smaller amounts. This gas is released in such large quantities from the soil that the supply in the atmosphere over the earth is maintained at a constant amount.

Decomposition by micro-organisms within the soil is the reverse of the process represented by plant growth above the soil. Growing plants using the energy of the sun, convert carbon, nitrogen, and all other elements into complex compounds. The energy stored up in these compounds can be used more or less completely by the

micro-organisms whose activity within the soil makes nutrients available for a new generation of plants. Organic matter thus supplies the "life of the soil" in the strictest sense.

**Organic Matter Content of Mineral Soils.** The percentage of organic matter in soils varies over a wide range. Some coarse sandy and gravelly soils contain only a fraction of 1 per cent. ; peaty soils, in contrast, may have as high as 90 or 95 per cent. of organic matter. In productive mineral soils, the range is about 2 to 5 and occasionally 6 per cent. of organic matter by weight. Around 4 per cent. may be regarded as a desirable proportion of organic matter in soils of moderately high potential productivity.

✓ A certain indefiniteness exists in the terminology applied to soil organic matter. Whilst many writers use humus as synonymous with organic matter, others have applied the term to a definite fraction. This confusion has led to the abandonment of the term humus by many writers. G. W. Robinson is of the opinion that the name humus might be conveniently retained for the organic matter of the soil which has been decomposed and has lost its original structure. Humus would thus exclude recognizable fragments of plant materials which have not yet become part of the characteristic organic matter of the soil.

✓ Some sedimentary rocks contain organic matter ; but the organic matter in such cases, though doubtless originally similar to that in the soil, has become considerably modified by secular changes. Whilst the soil organic matter is the habitat of a complex micro-flora and fauna, the organic matter of such sediments as bituminous shales and coal is completely devoid of microbiological activity, and, if brought under the influence of soil micro-organisms, is as indifferent to their activities as to much inert mineral matter.

✓ The altered organic matter of such sediments as shales and coals also differs from soil organic matter in the much higher proportion of carbon which it contains. Whilst soil organic matter contains from 55 to 60 per cent. of carbon, the organic matter of shales contains much higher proportions ; and in the extreme case of anthracites, is almost entirely carbon.

✓ In common with other types of matter in the colloidal state the soil organic matter exhibits absorptive and catalytic powers to an unusual degree. ✓ In its capacity to attract and hold water, gases and salts in solution, humus greatly excels the mineral colloids; its power to hasten reaction is also much greater.

## THE BIOLOGICAL NATURE OF THE SOIL

The life of the soil plays such a prominent and indispensable rôle in the changes constantly occurring, that no discussion of the organic matter is complete without its consideration.

Humus is a requisite for the biochemical processes of the soil and is, with its associated moisture, the medium in which soil organisms fulfil their life-cycles. The presence of humus and its living population is the distinctive character of a soil. Indeed it can even be said that practically all natural soil reactions are directly or indirectly biochemical in nature. The soil organisms govern by their enzymic activity the nature of the humus and control the volume of carbon dioxide produced. The appearance of ammonium compounds in the soil is also due mainly to their action. The production of nitrates and sulphates, indispensable sources respectively of nitrogen and sulphur for higher plants is governed by soil organisms. The provision of suitable nitrogenous nutrients for plants would be restricted and also the weathering of soil particles (to provide other mineral nutrients) would be retarded in the absence of dissolved  $\text{CO}_2$  in the soil water. The soil without its unnumbered hosts of organisms could not be the pulsating, dynamic and catalytic mass we know.

## THE COLLOIDAL COMPLEX

Humus occurs in close association or perhaps loose chemical combination with clay. This clay-humus association is called the colloidal complex, and is the seat of most of the chemical and biological activity of the soil.

**The Amount and Nature of the Colloidal Complex.** We may now have a set of soils containing the same proportion of colloidal matter but differing totally in properties, for in one the complex may be mainly siliceous clay, giving us a tenacious heavy soil, whilst in another the complex may be sesquioxidic clay, giving us friable soil, such as the lateritic soils of the tropics.

The colloidal complex acts as a weak insoluble acid that can react with bases ; in nature, principally with lime. The extent to which the acid colloidal complex is combined with bases has a profound effect on the general character of the soil. On the one hand, we have acid soils, in which the acidity of the colloidal complex is at maximum owing to lack of bases ; on the other hand, we have soils in which the soil acids are neutralized by combination with bases, and excess bases are present as carbonates, giving the soil an alkaline reaction.

**The Soil Solution.** It must be noticed that the soil, as we examine it in a dried laboratory sample, differs in important respects from the soil in the fields. In the latter case we must also include in our view the soil solution and the soil air. The soil solution, the moisture actually present in the soil, is the dilute aqueous solution from which, by absorption through their roots, plants obtain their nutrient requirements.

As the soil-water circulates through the intimately mixed mass of decomposing mineral and organic matter, it of necessity becomes a solution bearing at least traces of every element present in the soil. However, the mistake is often made of considering this soil solution in its relationships to higher plants as a simple water culture such as is used in botanical laboratories. The latter presents a continuous liquid body not greatly influenced by undissolved solids and homogeneous both physically and chemically. The soil solution, however, is in marked contrast. It is widely disseminated through the soil and exists, in part at least, in minute subdivision. Moreover, it suffers intense adsorption as it contacts the immense surfaces exposed by the colloidal solids. This means that some of the solution is at the colloidal interface, while part is relatively far away. Some is held tenaciously by the soil particles and has little movement, while some can move freely from place to place in the soil. Also the concentration due to the adsorption of the solute is greater in the immediate neighbourhood of the colloidal surfaces. The soil solution may therefore be characterized as heterogeneous in position, in movement, and in concentration.

Moreover, the soil solution is highly dynamic both as to amount and concentration. Rain, evaporation, and plant action obviously tend to vary its total amount. When such fluctuations are accompanied by varying rates of solution and losses of nutrients to higher plants and to drainage, rapid and often violent changes in concentration are sure to occur. Additions of fertilizers, lime, and farm-manure intensify rather than weaken these dynamic tendencies.

The composition of drainage waters may give us some indication of the relative proportions of different constituents in soil solutions, although the former may be considerably more dilute. It is not, however, possible to obtain the composition of soil solution by multiplying drainage water figures by a factor, because the solubility relationships are exceedingly complicated mainly on account of the presence in the soil of active colloidal material as above mentioned.

**The Soil Air.** In a natural soil we must take into account the soil air. This differs from atmospheric air in two important respects. In the first place, it is usually saturated with water vapour, and in the second place it may contain a much higher proportion of carbon dioxide than does the atmosphere.

The carbon dioxide in the soil air originates from the respiration of plant roots and from the decomposition of organic matter in the

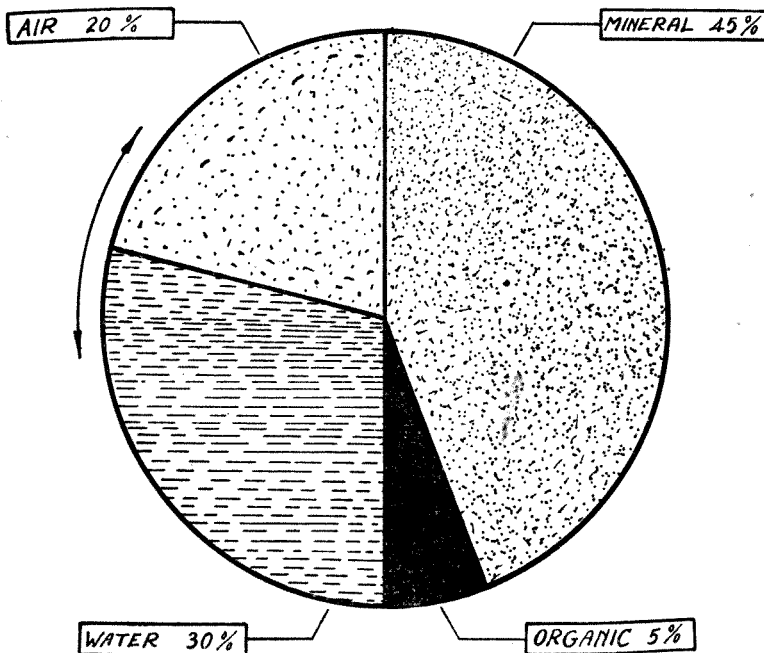


Fig. 4. Diagram showing the volume composition of a loamy soil when it is in optimum condition for plant growth.

soil. It varies from soil to soil, and varies from time to time in the same soil according to the intensity of carbon dioxide production. Carbon dioxide formed in the soil dissolves in the soil moisture, and there is thus a shifting equilibrium between dissolved carbon dioxide and free carbon dioxide in the soil. The dissolved carbon dioxide reinforces the solvent action of the soil moisture on the mineral matter of the soil, and thus plays an important part in weathering, and in rendering available the plant nutrients.

**The Volume Composition of Soil.** Once the identity of the four soil constituents is established even in a general way, the question

of their relative proportions becomes urgent. For simplicity of statement the representative surface soil may be considered to contain by weight approximately 4 per cent. of organic matter and 96 per cent. of mineral material. But this leaves entirely out of consideration the air and water, a serious omission since these constituents have so much to do with the activity of a normal soil. In giving a true quantitative concept of soil composition, the volume basis of representation must be used.

A representative silt loam surface soil when in optimum condition for plant growth contains approximately 50 per cent. of solids and 50 per cent. of pore space. The pore space will be somewhat less for sandy soils and somewhat greater for soils of a more clayey nature. The 50 per cent. of solid space is occupied by about 45 per cent. of mineral and 5 per cent. of organic substances by volume. At optimum moisture for plant growth the 50 per cent. of pore space possessed by this representative silt loam is divided roughly equally between air and water. It is, of course, subject to great fluctuations under natural conditions, depending on the weather and other factors (*see* Fig. 4).

In presenting such an arbitrary volume representation, it must be emphasized that the four main components of the normal soil exist in a finely divided and very intimately related condition and that very complex reactions occur with surprising ease and rapidity within and between the groups. Interface reactions are especially important and unless such interactions take place, this complex heterogeneous mass cannot long remain in a condition, either physically or chemically, to support plant life.

## CHAPTER 3

### *Origin of Soils*

THE Russian pedologists were the pioneers in studying the various processes which are involved in the making of soils, and it has become increasingly clear from their work, and the work they have inspired in other countries, that in order to understand any particular soil area it is necessary to have some conception of the processes which have been, and still are, going on ; and of the way in which the groups of soil-forming materials are behaving.

Soils are natural media for the growth of plants. They are mixtures of fragmented and partly or wholly weathered rocks and minerals, organic matter, water, and air, in greatly varying proportions, and have more or less distinct layers or horizons developed under the influence of climate and living organisms. The cross section of horizons from the surface to the parent material is known as the soil profile. The degree of profile development is dependent on the intensity of the activity of the different soil-forming factors, on the length of time they have been active, and on the nature of the materials from which the soils have developed. Soils are dynamic in character—they are constantly undergoing change—but they normally reach a state of near equilibrium with their environment, after a long period of exposure to a given set of conditions, and they may change but little during periods of hundreds or even thousands of years unless there is a change in the environment.

#### WEATHERING PROCESSES

A study of weathering and of the soil materials that result therefrom is, not only interesting in itself, but it is also a necessary introduction to soil formation and classification.

We can distinguish two types of weathering, namely :—

- (1) Physical or mechanical.
- (2) Chemical.

**(1) Physical Weathering.**

In physical or mechanical weathering, no chemical changes are involved but merely disintegration, the same kind of change that would occur if the rock were simply crushed down to fragments. Physical weathering can take place in a number of ways, by alternate expansion and contraction consequent on temperature changes, by frost action, by the abrading action of glaciers, by running water, or even by the blast of sand blown by wind. They can be studied in more detail in any textbook of geology.

**(2) Chemical Weathering.**

In chemical weathering, more profound changes occur. Minerals present in the weathering rock are decomposed and new substances are formed. Here we must distinguish between unweatherable minerals. The commonest unweatherable mineral is quartz, which survives unchanged except for physical comminution, through successive weathering cycles. Other unweatherable minerals are magnetite and certain other oxides of iron and titanium.

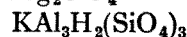
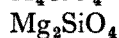
The most important group of weatherable minerals, however, is the mineral silicates. There have been many obscurities about their chemistry, because their sparing solubility, their high melting point, and their manifest complexity made the study of them, by the methods applicable to soluble salts, impossible. Their structure is being elucidated by modern X-ray work.

The alliance of silicon and carbon which is indicated in the periodic classification of elements has suggested that the multiplicity of silicates may be explained on the same lines as the large and indefinite number of carbon compounds. Starting with the formula of orthosilicic acid,  $\text{Si}(\text{OH})_4$ , the formulae of a large number of hypothetical acids can easily be constructed. Orthosilicic acid,  $\text{H}_6\text{Si}_2\text{O}_7$ , for example, follows from the union of two molecules of  $\text{Si}(\text{OH})_4$  and the elimination of the elements of a molecule of water. Starting with metasilicic acid  $\text{H}_2\text{SiO}_3$ , there follow in a similar way metadisilicic acid  $\text{H}_2\text{Si}_2\text{O}_5$ , metatrisilicic acid  $\text{H}_4\text{Si}_2\text{O}_8$ , etc. Almost all the natural silicates may be regarded as salts of these hypothetical silicic acids, for example :—

Salts of orthosilicic acid

Olivine

Muscovite



Salts of orthodisilicic acid	$H_6Si_2O_7$
Barysilite	$Pb_3Si_2O_7 \dots$
Salts of othotrisilicic acid	$H_8Si_3O_{10}$
Akermanite	$Ca_4Si_3O_{10}$
Salts of metasilicic acid	$H_2SiO_3$
Enstatite	$MgSiO_3$
Tremolite	$CaMg_3(SiO_3)_4$
Salts of metadisilicic acid	$H_2Si_2O_5$
Petalite	$LiAl(Si_2O_5)_2$
Salts of metatrisilicic acid	$H_4Si_3O_8$
Orthoclase	$KAlSi_3O_8$
Albite	$NaAlSi_3O_8$

*Silicates containing aluminium.* Very many natural silicates contain aluminium and from the viewpoint of soil chemistry these are very important. According to older views the alumina in these compounds function as a base, orthoclase felspar being regarded as a double silicate of potassium and aluminium. Alumina, however, is amphoteric ; it functions as a base in the presence of strong acids forming aluminium salts, and as an acid in the presence of strong bases, forming aluminates. In the presence of silicic acid—a very weak acid—and potash and other strong bases, it is most likely that alumina behaves as an acid and that orthoclase felspar, for example will not be a potassium aluminate silicate, but a potassium aluminosilicate. This is a prevalent view of the constitution of these silicates and is mainly due to Vernadsky, who has been able to account for all the aluminium silicates by postulating five groups of aluminosilicic acids, whose empirical formulae are :—

1. Aluminosilicic acid       $H_2O.Al_2O_3.SiO_2$     or  $H_2Al_2SiO_6$
2. Aluminodisilicic acids     $H_2O.Al_2O_3.2SiO_2$    or  $H_2Al_2Si_2O_8$   
 $2H_2O.Al_2O_3.2SiO_2$    or  $H_4Al_2Si_2O_9$   
 $3H_2O.Al_2O_3.2SiO_2$    or  $H_6Al_2Si_2O_{10}$
3. Aluminotrisilicic acids     $H_2O.Al_2O_3.2SiO_2$    or  $H_2Al_2Si_3O_{10}$   
 $3H_2O.Al_2O_3.3SiO_2$    or  $H_6Al_2Si_3O_{12}$
4. Aluminotetrasilicic acid    $H_2O.Al_2O_3.4SiO_2$    or  $H_2Al_2Si_4O_{12}$
5. Aluminohexasilicic acids    $H_2O.Al_2O_3.6SiO_2$    or  $H_2Al_2Si_6O_{16}$   
 $3H_2O.Al_2O_3.6SiO_2$    or  $H_6Al_2Si_6O_{18}$   
 $9H_2O.Al_2O_3.6SiO_2$    or  $H_{18}Al_2Si_6O_{24}$

Regarding the soil-forming minerals as a whole, there are three outstanding groups of constituents which are of fundamental importance in soil chemistry, namely :—

1. Strong bases. Lime, magnesia, soda and potash are predominant.
2. Sesquioxides, i.e., oxides of iron and aluminium.
3. Silica.

Physical and chemical weathering of the soil-forming minerals can proceed at the same time, but we may regard physical weathering as facilitating chemical weathering, since by breaking down rocks it exposes fresh surfaces to chemical attack. Chemical weathering is at minimum under desert conditions, owing to absence of moisture, and under polar and alpine conditions owing to low temperature. It is most intense under humid tropical conditions. It is not uncommon in the tropics to find one hundred feet or more of material, weathered in place, overlying its parent rock.

Chemical weathering is effected through :—

- (1) Solution. (2) Carbonation. (3) Oxidation. (4) Hydration.
- (5) Hydrolysis.

**(1) Solution.** In chemical weathering water acts as a solvent or as an agent of decomposition. The action of water as a solvent is confined mostly to gases and solids. In connection with the dissolution of gases we must remember that atmospheric precipitations are continuously in contact with the air during their long descent to the earth, and after reaching the soil remain in contact with the soil atmosphere for a considerable time and over a large surface. Nernst has shown that when water comes into contact with several gases, the amount of each gas dissolved is the same as if the others were not present. The solubility of gases varies considerably, N, O and CO<sub>2</sub>—the gases involved in weathering—being relatively insoluble. Of these CO<sub>2</sub> and O are the most soluble. Water also dissolves some ozone and ammonia from the air.

The solubility in water of the solid materials varies considerably. Pure water scarcely dissolves the rock-forming minerals at all, but some minerals (e.g., CaCO<sub>3</sub> and MgCO<sub>3</sub>) are notably soluble in water containing carbonic acid, with which they form easily soluble bicarbonates. This is usually regarded as pure solution, though actually solution is accompanied by chemical reaction. Similarly, carbonic acid converts slightly soluble phosphates into less insoluble compounds. Finally, recent work has shown that even the least soluble minerals—e.g., silicates—dissolve slightly in pure water and only

afterwards are decomposed by water or carbonic acid or other materials dissolved in the water.

✓ Let us now enquire what active substances are contained in the precipitation water which causes chemical weathering. We have seen already that water absorbs more oxygen and even more carbon dioxide than nitrogen. The role of oxygen in weathering is to oxidise oxidisable compounds. Most of the rock-forming minerals are, indeed, fully oxidised already, so that oxygen has no effect upon them; however, we find compounds of iron and manganese which are still oxidisable, as is also dead organic matter.

Opinions differ with regard to the role of dissolved  $\text{CO}_2$ , to which great importance was formerly attributed as a factor in chemical weathering. It has now been shown that the presence of water is in itself sufficient explanation for most of the chemical reactions ensuing and that the  $\text{CO}_2$  found in water occurs mostly (e.g., 99.44 per cent.) as an anhydride, only a very slight proportion (e.g., 0.56 per cent.) dissolving in the form of  $\text{H}_2\text{CO}_3$ , the latter being approximately 91 per cent. dissociated into  $\text{H}^+$  and  $\text{HCO}_3^-$ . There can be no doubt, however, that carbonic acid water reacts with both carbonates and silicates to a far greater degree than these conditions would lead us to expect. The explanation of this is that the hydrogen ions consumed are continuously replaced so long as any  $\text{CO}_2$  remains absorbed in the water. This explanation illustrates the importance of carbonated water as a factor in the chemical weathering of minerals. Particularly important is the action of carbonated water in dissolving alkaline-earth carbonates ( $\text{CaCO}_3$ ,  $\text{MgCO}_3$ , and dolomites) and ferrous carbonate ( $\text{FeCO}_3$ ) which are frequently found among the decomposition products of silicates. It is highly probable, therefore, that carbonated water is an important factor in their weathering too.

It has long been known that the air contains certain quantities of ammonia, and nitrogen tri- and pentoxides. Boussingault found that the quantity of combined nitrogen brought down on 1 hectare by the annual rainfall is altogether 2.7 kilogrammes (1.82 kilogrammes ammonia nitrogen and 0.88 kilogramme nitric acid). The figure found at Rothamsted is higher. It is about 3.6 kilogrammes.

Of the chlorides,  $\text{NaCl}$  especially is found in air, and therefore in rain, but the bulk of it is dissolved from solid rocks. According to Clark, the proportion of  $\text{Cl}$  in the eruptive rocks of the lithosphere averages 0.063 per cent., and in calcareous rocks 0.02 per cent. This is the origin of all the chlorides in fresh water and accumulating in

sea water. Chlorides do not, however, play any important role in chemical weathering. ✓

✓ Sulphuric acid and sulphates originate either from the pyrites and marcasite of rocks or from organic sulphur by the reduction of organic substances. From organic sulphur certain bacteria evolve  $H_2S$  which precipitates iron in the form of ferrous sulphide. By contact with the air  $H_2SO_4$  is produced. Although the quantity of the sulphuric acid thus produced is usually not large, the distribution of sulphates in soils and water proves that this process is fairly general. And since it is a strong acid, even a small quantity of sulphuric acid can play an important role in the process of chemical weathering. In dry regions gypsum accumulation is by no means rare. Under humid conditions, however, their greater solubility renders sulphates more liable than carbonates to leaching, except where the subsoil is impermeable. In Finland, for instance there are salty soils containing large proportions of aluminium sulphate. These are impermeable peaty soils, so that there is an accumulation of sulphates, while as a result of hydrolysis the aluminium sulphate produces a highly acid reaction.

✓ Finally the humus substances, and in particular the humic acids produced during the decomposition of dead organic matter, are also active factors in the weathering of rocks. We shall discuss their nature later. Here we shall only point out that as acids they increase the hydrogen-ion concentration and thereby accelerate chemical decomposition of minerals, and as protective colloids forming emulsions they increase the stability of colloidal dispersions and thereby the mobility of the insoluble weathering products. •

✓ Thus, from the rocks certain constituents are brought into solution, and they eventually appear in the streams and rivers. These include  $Ca(OH)_2$ ,  $NaOH$ ,  $KOH$ , and silicic acid. Aluminium hydroxide is an important constituent and ferric hydroxide is also present. All the elements are therefore available from which the clay minerals may be synthesized. The dilutions of all these constituents are high, thus crystallization will be slow and it may be hindered by such temporary associations as can be formed by the mutual coagulation of positively charged aluminium hydroxide with negatively charged silicic acid sols.

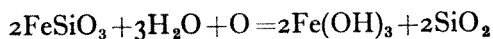
Where the river empties into the sea, there is a high concentration of salts and the colloidal material brought down by the rivers is coagulated. It is deposited as mud, along with the unchanged

mineral grains derived by purely mechanical action from the original rocks. In such deposits the rebuilding of aluminosilicate structures certainly proceeds, but at a slow rate because of the much smaller solubility of their chief constituents in sea water compared with river water. The sediment finally produced has normally a higher ratio of silica to bases than the rocks from which it is derived. In this way clays of secondary origin are formed.

(2) **Carbonation.** The readily soluble hydroxides formed by weathering are easily washed away from the soil, but they react further with the carbon dioxide of the air or of the soil water. In this case, calcium carbonate will be formed, and it will either accumulate in the soil or be washed away according to whether or not there is sufficient water in circulation. In a similar manner carbonates of magnesium and other metals are formed in the soil material or in the soil itself. Carbonation is most rapid in regions of high rainfall, but the products of carbonation are removed so rapidly in such areas that the soil will actually contain fewer carbonates than that developed in semi-arid regions.

If organic matter should accumulate, the influence of carbon dioxide becomes intense and carbonation is more pronounced. Thus plants and animals may exert a chemical influence, in the preparation of soil materials, that is more important than their physical activities.

(3) **Oxidation and Reduction.** Changes in the state of oxidation of some of the elements, particularly of iron and manganese, take place under certain soil conditions. Mineral powders exposed to moderately dry air undergo little or no change. When they are enveloped by water, however, hydrolysis converts some of the ferrous iron and the manganous form of manganese into slightly soluble hydroxides, of which the iron compound normally occurs in the greater proportions. These compounds are capable of taking up oxygen from the air to form more highly oxidised compounds of extremely low solubilities. Such oxidation is often evident from the formation of scums or crusts which have the characteristic colour of iron rust and consist primarily of ferric hydroxide, more or less dehydrated. Oxidative processes, broadly speaking, affect only ferrous compounds. Certain ferromagnesian compounds contain ferrous iron, which, in the presence of air and moisture, is capable of being oxidized with the production of hydrated ferric oxide, e.g.

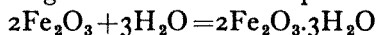


Iron pyrites and marcasite yield by oxidation hydrated ferric oxide and sulphuric acid :—



Under certain soil conditions a reverse action takes place. The mere absence of air is not sufficient to cause these compounds to lose oxygen. However, certain organisms associated with the decomposition of organic matter are capable of extracting oxygen from such compounds as ferric hydroxide when air is excluded by water. This change produces an iron compound of greater solubility. When soils are waterlogged for a considerable period significant proportions of the iron may be reduced. These oxidation and reduction changes may play an important role in soil-profile development and in the formation of parent material from rocks.

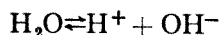
(4) **Hydration.** Water functions as a weathering agent in another way—as water of combination or of crystallization. The process is called hydration. Many minerals, especially the olivine, feldspar, and mica groups, are so affected. They become soft and lose their lustre and elasticity by reason of this chemically combined water and an increase of bulk occurs. As a result minerals so affected succumb readily to physical and chemical forces. The simplest example of the phenomenon is the change of haematite to limonite, which occurs to a greater or less degree wherever the sesquioxide is present.



Haematite (red) + water = Limonite (yellow)

When the products of hydration dry out due to varying weather conditions, dehydration may occur. Thus limonite may readily be reduced to a lower hydrate or to haematite. Red and yellow in all gradations and shades may, therefore, be expected in soil materials where vigorous oxidation and hydration have been possible.

(5) **Hydrolysis.** We must differentiate between the action of water as a solvent and as a decomposing agent ; water possesses the property of dissociating slightly into its free ions. According to Kohlrausch and Heydweiler, ten million litres of pure water at a temperature of 22° C. contains 1 gramme of H ions and 17 grammes of OH ions, equal to 1 gramme-molecule of water. This so-called electrolytic dissociation of water increases considerably with rise in temperature. The reaction may be expressed by the following equation :



where  $\text{H}^+$  represents hydrogen ions charged with positive electricity,

and  $\text{OH}^-$  negatively charged hydroxyl ions. Electrolytic dissociation follows the law of Mass Action—i.e.,

$$\frac{(\text{H}^+) \times (\text{OH}^-)}{(\text{H}_2\text{O})} = K$$

*The Effect of Hydrolysis on the Solubility of Silicates.* The bulk of the earth's crust consists of silicates, which consequently also form the main parent material of soils. According to recent theories the chemical weathering of silicates consists in the alkali and the alkaline-earth cations ( $\text{K}^+$ ,  $\text{Na}^+$ ,  $\text{Ca}^+$ ,  $\text{Mg}^+$ ) going into solution with hydroxyl ions in a state of strong dissociation. In the presence of abundant  $\text{CO}_2$ , the less soluble and less dissociated  $\text{Ca}(\text{OH})_2$  and  $\text{Mg}(\text{OH})_2$  form easily soluble bicarbonates, thus considerably increasing the solution of Ca and Mg cations. Carbonic acid here plays a peculiar role of its own. The Fe and Mn in silicates are usually present in bivalent form and their hydroxides, being insoluble in water, are precipitated unless the presence of abundant carbonic acid causes the formation of bicarbonates which are leached out. In contact with oxygen, however, ferric and manganic oxides and hydroxides are precipitated.

The fate of the different constituents may vary considerably according to the conditions. The most resistant are Si and Al, as their oxides and hydroxides are practically insoluble. Hence they usually accumulate in the residue from the weathering of the silicates, whereas the others are more or less leached out.

### General Results of Hydrolysis

However we may conceive the process of hydrolysis, certain general consequences may be noted :—

(1) **De-silicification.** Comparison of weathered materials with their parent rocks generally reveals a loss of silicic acid in the weathering process. The silicic acid is removed by percolating waters, to a great extent in the form of silicates of the alkalies and alkaline-earths. It is significant that river waters, which contain the material lost by solution in the weathering processes, contain an excess of silicic acid over sesquioxides. In arid and semi-arid regions incomplete leaching may prevent the removal of silicic acid liberated by hydrolysis. In such cases the weathering-complex is characterized by a high content of silica.

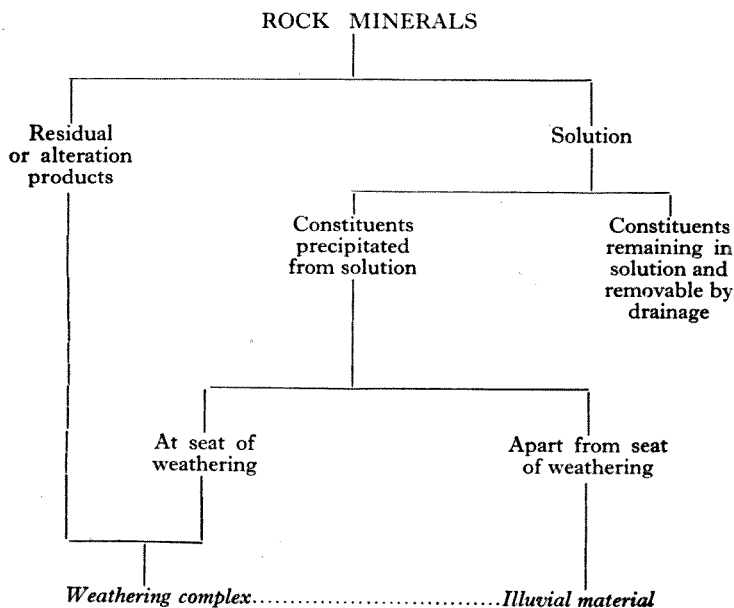
(2) **De-alkalization.** De-alkalization occurs during hydrolysis. Comparison of fresh rocks with their weathered products reveals a

general loss of calcium, magnesium, potassium, and sodium. Exceptions to this rule occur in arid regions, where alkali and alkaline-earth salts may accumulate, giving rise to saline or alkaline soils.

**(3) Formation of new substances.** Hydrolysis results in the formation of new substances, either by modification of the original materials or by a partial re-synthesis of the products of decomposition. These substances are collectively referred to as the weathering-complex, the clay complex, or the inorganic soil colloid. They constitute the greater part of the clay fraction in mechanical analysis and are almost entirely found in that fraction.

Essentially, chemical weathering involves two phases, namely, (a) the disappearance of certain minerals, and (b) the formation of secondary products. Some of the secondary products may originate by alteration of the parent minerals, whilst other products may originate by precipitation from solutions containing the soluble products of weathering. Such precipitation may occur at the seat of weathering, or apart from the seat of weathering after transport by moving water. Material precipitated at the seat of weathering may be mixed, or even enter into combination, with residual products.

The processes may be represented diagrammatically as follows :



The weathering-complex, representing that portion of the soil which is of secondary origin, may include residual or alteration products and material precipitated in situ from soluble products of chemical weathering. It may also include material transported from elsewhere and reprecipitated.

### THE PLACING OF SOIL MATERIALS AND THE RESULTING FORMATIONS

Two groups of soil materials, designated as sedentary and transported, are usually recognized.

#### (A) Sedentary Materials.

Residual materials are of wide distribution on all the continents. Large areas occur in the United States, particularly in the eastern and central parts, although great expanses are found in the West as well. As might be expected, a great variety of soils occupy the regions of residual debris, since climate, the determining factor in soil characterization, varies so radically over these great areas.

#### (B) Transported Materials.

Transported materials were brought to their present position by such agencies of transportation as gravity, water, ice, and wind. These agencies have been actively shifting soil materials about continuously throughout the ages.

It is conceivable that soil material may at one time or another have been transported in turn by several of these agencies. Materials are classified, however, under the agency that was responsible for their present location. A few examples may be helpful. Ice sheets picked up and moved forward colluvial material which in turn became glacial debris. The finer portion of this may have been assorted and carried far beyond the limit of the ice by streams, the deposit then being classed as alluvial. During dry periods, the wind picked up and spread this fine alluvial material over the upland where it now rests as aeolian material.

Transported soil materials can be divided into :—

- (1) Colluvial.
- (2) Alluvial.
- (3) Marine.
- (4) Lacustrine.
- (5) Glacial.
- (6) Aeolian.

(1) **Colluvial Materials.** Colluvial materials were moved from their point of origin primarily by gravity. The familiar example is the talus, or rock debris, at the base of cliffs or slopes. Strictly colluvial deposits are confined to areas of steep topography and, more particularly are usually so coarse and dry that they do not ordinarily develop into productive soils.

Soil material developed from colluvial accumulation is usually coarse and stony, as physical rather than chemical weathering has been dominant. Such deposits are not of great importance because of their small area, their inaccessibility, and their unfavourable physical and chemical characteristics.

(2) **Alluvial Materials.** Alluvial materials were moved to their present location by streams. The carrying power of streams, which is surprisingly great, is profoundly affected in a number of ways. If a grain of sand that has a specific gravity of 2.65 in the air is placed in water, it loses effective weight equal to that of the water it displaced. In water, therefore, it has an effective specific gravity of only 1.65 and may be carried easily by streams.

In addition, there is the influence of the velocity of the current of the stream itself. The weight of individual particles borne in suspension by a current of water varies as the sixth power of its velocity. Doubling the velocity, therefore, enables a current to carry particles 64 times as heavy as before, and trebling increases by 729 times the weight of particles the faster current can carry. In other words, if a current is carrying particles weighing 1 gram, trebling the velocity increases the weight of particles that can be carried to 729 grams. This explains the well-nigh unbelievable transporting power of streams with steeply sloping beds in hilly and mountainous areas. Under these conditions, much additional coarse material is pushed and rolled along on the bed of streams.

The quantity of material a current can carry varies approximately as the fifth power of its velocity. Doubling its velocity, consequently enables a stream to carry 32 times, and trebling 243 times, as much total soil material as before. This information helps to explain the ability of streams to carry the immense quantities of soil material that they actually transport at flood stage.

Certain large rivers, of which the Mississippi and the Nile are notable examples, deposit large quantities of soil materials in the sea. The Mississippi deposits its material in the Gulf of Mexico where it is not disturbed materially by shore currents. Upon contact

with the salt water, the fine materials carried are precipitated and thus build up a delta. Delta materials often lack drainage. If drainage can be provided, such deposits often develop into highly productive soils. In a similar way, small deltas develop where sizable streams enter inland lakes.

There are three general classes of alluvial deposits :

- (A) Flood plain deposits.
- (B) Alluvial fans.
- (C) Deltas.

(A) *Flood plain deposits.* Flood plain deposits are found to a certain extent beside every stream, the greatest development in the United States occurring along the Mississippi. This area varies from forty to sixty miles. The soils derived from such sediments are very rich, but, if they are first bottoms, they require drainage and protection from overflow.

(B) *Alluvial fans.* Where streams descend from mountains or plateaus, a sudden change in gradient usually occurs as the stream emerges at the lower level. A deposition of sediment is thereby forced, giving rise to alluvial fans. They differ from deltas in their location and in the character of their debris. Fan material is generally gravelly and stony, more or less porous and well drained.

Alluvial fan debris is found over wide areas in arid and semi-arid regions and the soils therefrom when irrigated and properly handled have proved very productive. Even in humid regions such deposits often occur in large enough areas to be of considerable agricultural importance.

(C) *Deltas.* Much of the sediment carried by streams is not deposited in the flood plain but is discharged into the body of water to which the stream is tributary. Unless there is sufficient current and wave action, the suspended materials accumulate, forming a delta. Such delta deposits are by no means universal, being found at the mouths of only a small proportion of the rivers of the world. A delta is generally a continuation of the flood plain, and is not only clayey in nature but likely to be swampy as well.

Delta sediments where they occur in any considerable acreage are rather important. The deltas of the Mississippi, Ganges, Po, Tigris, and Euphrates rivers are striking examples. Egypt bespeaks the fertility of soils originating from both delta and flood-plain materials.

This soil material has been worn and triturated by a number of

agencies. First, the weathering and erosion necessary to throw it into stream suspension were sustained. These were followed by the sorting and solvent action of the stream itself. Next the sediment was swept into the ocean to be deposited and stratified, possibly after being pounded and eroded by the waves for years. At last came the emergence above the sea and the final action of the forces of weathering. The latter effects are of great moment since they determine the topography and, to a certain extent, the chemical nature of the resultant soil material.

(3) **Marine Materials.** As already indicated, the waves on ocean shore lines have produced large quantities of relatively coarse soil materials because the fine particles were carried away by currents. As relatively flat shore lines are elevated above high tide, these materials develop into soils. In certain areas, plants grow to the extent of forming organic deposits.

(4) **Lacustrine Materials.** In some places, the land surface slopes towards the ice. Upon thawing, the water accumulates as a lake. Glacial water and precipitations on the land contribute soil material of all sizes. Near the shore of some larger glacial lakes, streams deposit coarse materials as steep-faced deltas. The fine material is carried well out into such lakes and is finally deposited. This is called lacustrine material.

(5) **Glacial Materials.** In addition to producing a tremendous quantity of soil-forming material, glaciers pick up the previously formed residual soil material and mix it with freshly ground-up rocks. The debris carried by the glacial ice, therefore, is a highly variable mixture of old soil and freshly reduced rock material. Consequently, varying periods are required for the weathering of this debris.

When the ice disappears, the material it carried is left as a mantle of rock debris over the area the glacier had covered. The debris is a mixture of the fine and coarse materials. This heterogeneous deposit is variously called ground moraine, glacial debris or till, or boulder clay. The ground moraine, which is variable in thickness, parent material, and topography, is by far the most extensive of the glacial deposits.

As might be expected, the soils derived from such soil material are most heterogeneous. Such variation serves to indicate that the term glacial soil is of value only in suggesting the mode of deposition of

the soil materials. It indicates practically nothing as to the characteristics of the soil itself.

The glaciation in most cases has been a decided benefit, especially agriculturally. The levelling and filling actions have given a smoother topography more suited to farming operations. Also the soil materials thus supplied are geologically fresh and the soils derived therefrom are young. While it is difficult to show any consistent difference in total nutrients between the old residual and the younger glacial soils, it is generally admitted that glaciation has been a benefit to agriculture in that the soils have been rejuvenated and their crop-producing power raised. Here the chemical transformations are at a minimum in consequence of the low temperature, and the boulder clays primarily formed consist almost entirely of unchanged rock fragments. As might be expected, the particle size is greater than those found in the sedimentary clays and the clay minerals themselves are absent. Thus the glacial clays derived from primary rocks consist chiefly of felspar fragments varying in size from about 0.2 upwards. They possess notable reserves of bases, the greater part of which are only very slowly made available.

(6) **Aeolian Materials** have been transported to their present location by the wind, and consist mainly of very fine sand and silt and of volcanic dust. Sand dunes are, perhaps, the most familiar wind-deposited material. They consist of alternate depressions and elevations. Certain depressions from which the wind has removed the sand are known as blowouts. The mound- or ridge-like elevations are called dunes. Any obstruction, such as weed, a shrub, or a tree may check the wind and thus start dune formation. The movement of sand dunes is irresistible. In Dune Park in Indiana (U.S.A.), the sand buried forests. Later the sand moved on, and the remains of the trees were resurrected. Likewise, productive land is often buried under sand of little value.

Aeolian materials are greatly developed in northern France and Belgium, and along the Rhine in Germany, where they give rise to important soils in the valleys that are tributary to that river. Silesia, Poland, southern Russia, Bohemia, Hungary, and Roumania have deposits of this highly fertile soil material. In China loess, or aeolian material, is found over a very large part of the valley of the Hwangho, a region probably larger in area than France and Germany combined. The thickness of the deposit is variable, ranging from a few feet to even a thousand in places.

## DEGREE OF WEATHERING OF SOILS

The degree of weathering is reflected in the character of the different soil fractions. At the one extreme are highly weathered soils of the humid tropics. In such soils, the only original minerals are those which are resistant to hydrolysis, such as quartz, magnetite, etc. Where the parent rock contains no unweatherable minerals, the resulting soil may consist entirely of the weathering-complex. Some soils on analysis may yield up to 90 per cent. of clay.

The removal of silicic acid, alkalies, and alkaline earths in weathering proceeds to varying stages according to the conditions which obtain. In humid temperate climates there is some evidence that a complex is formed with a molecular ratio of silica to sesquioxides of 2.0. Under humid tropical conditions it appears that desilicification can proceed further. The laterites which occur in many parts of the tropics consist, in extreme cases, almost entirely of hydrated sesquioxides and might be described as "dead soils."

In the less weathered soils of temperate and cool regions there is generally a considerable proportion of weatherable minerals such as feldspars, micas, and ferromagnesian minerals in the silt and sand fractions. As a rule, soils of secondary origin are more highly weathered, i.e., contain less weatherable material, than soils of primary origin. This is due to the fact that they have already been submitted to one or more cycles of weathering. It is indeed quite possible that, even in Northern Europe, soils may occur which consist simply of quartz and the weathering-complex.

An approximate indication of the degree of weathering of a soil may be obtained from the proportion of alumina in the clay fraction relative to the total amount of alumina present in the soil. Since the principal weatherable silicates are all complex silicates of alumina and other bases, it follows that in a completely weathered soil, no alumina will be found in that portion of the soil from which the clay or weathering-complex has been removed. Lateritic soils with concretionary alumina in the coarser fractions would, of course, be exceptions to this generalization.

In soils where the weathering has been partly physical, the non-clay fraction contains unweathered aluminosilicate minerals, and the proportion of clay alumina to total alumina may give an approximate measure of the extent to which chemical weathering has proceeded.

Similar reasoning may be applied to the distribution of ferric oxide between clay and non-clay, but its applicability to ferric oxide

is limited by the possibility of the occurrence of unweatherable iron minerals such as magnetite and by the readiness with which hydrated ferric oxide forms coarse concretions.

TABLE 2

*Degree of Weathering of Soils as shown by content of Alumina and Ferric Oxide in Clay and Total Soil*  
(G. W. Robinson and M. Richardson)

Soil	Ignited clay %	Per cent. Al <sub>2</sub> O <sub>3</sub> in		Degree of weathering %	Per cent. Fe <sub>2</sub> O <sub>3</sub> in		Degree of weathering %
		Clay	Total soil		Clay	Total soil	
Schistose subsoil, Wales	14.0	4.4	11.3	39.1	1.85	5.0	37.0
Shaly soil, Wales ...	21.0	7.05	17.5	40.3	2.55	7.6	33.5
Shaly sub-soil, Wales ...	19.5	6.5	19.7	33.0	2.3	7.4	31.1
Red Loam, E. Africa ...	35.5	13.3	18.0	73.9	5.6	9.8	57.1
Yellow soil, India ...	20.2	3.35	9.6	55.7	2.1	3.7	57.0
Alluvial soil, Holland ...	48.5	12.85	13.7	93.4	2.95	6.1	48.5
Chalk soil, England ...	28.5	4.3	5.0	85.6	2.2	3.5	63.5
Red clay loam, E. Africa	50.0	17.05	19.0	89.7	8.25	8.7	94.3

The figures show the marked distinction between the relatively juvenile Welsh soils, still in the early stages of chemical weathering and the alluvial and chalk soils in which, presumably, the material has been submitted to one or more cycles of weathering. The Indian yellow soil and the African red loam occupy an intermediate position, whilst the East African red clay loam is almost completely weathered. Like the Welsh soils, these are products of primary weathering, but the process has proceeded to a greater degree, particularly in the African red clay loam.

H. Jenny has proposed to use the K/Na ratio in soils as a measure of the degree of weathering. Since sodium is more readily leached than potassium, the tendency is for the K/Na ratio to widen, with the maturity of development.

Soils in the early stages of development, desert soils, and the soils of the arctic and alpine regions are predominantly the result of physical weathering. They are generally characterised by the presence of large proportions of coarse material. They are termed skeletal soils.

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## CHAPTER 4

### *Inorganic Soil Colloids*

IN the scientific study of soils, chemical interest and experimental difficulties increase as the particle size of the material decreases. The larger particles are usually considered as the soil skeleton and on account of their comparatively small surface, are chemically inactive in contrast to the "active" soil colloids.

With the exception of the very purest sea-shore or wind-borne sands, all soils contain particles of colloidal size. These are conveniently divided into two large groups, the inorganic or mineral colloids and the organic or humus colloids.

The inorganic colloids which are often described as clay colloids, were described wrongly in the past as necessarily indefinite in composition and non-crystalline and very scanty progress was made in elucidating the character of clay. Considerable confusion has also arisen from the circumstance that the name "clay" is used in at least four different senses by different groups of workers. Soil chemists use it for all the mineral material of the soil, the particles of which, if spherical, would be below 0.002 mm. in diameter. Ceramic chemists, on the other hand, allow a much larger limit of size (0.01 mm. diameter) but they restrict the name to a group of minerals of which kaolinite is the type. Geologists use the word in a third sense, and road engineers in a fourth. New names have at times been proposed to distinguish these substances but none has proved acceptable. Finally the mineralogist uses the word "clay" to denote a certain group of minerals containing oxygen, silicon and aluminium or iron as the major constituents. There is no restriction as to particle size.

It has been recently proposed to replace the term "clay" in its agronomic sense by the word "agrargile" and leave the use of the term "clay" to the mineralogist.

The colloidal properties are not strictly confined to the clay

fraction. They become more pronounced as the particles become smaller, but there is no stage at which they suddenly appear. Beginning with the silt fraction they appear gradually as the particles become finer, though not all at the same stage nor do they all increase in the same way with increasing fineness. Some colloidal properties, such as base exchange, are often shown by the silt fractions, while others, like the power of forming gels, are shown by the very fine particles and not by the coarser ones.

The inorganic colloids of soils, however, fall into three classes :—

- (1) The clay.
- (2) The hydrated oxides.
- (3) The phosphates.

We know little as yet about the occurrence of the hydrated oxides and the phosphates in soils and it is only in recent years that the clay minerals have begun to be identified with any precision.

### (1) THE CLAY

We must briefly consider the various practical uses of the word "clay," after considering their scientific uses before. A farmer frequently refers to a whole soil as a clay, meaning that it is heavy to work, sticky in wet weather and lumpy in dry weather. A brick maker would only describe a clay as a subsoil which could be baked to form bricks. A potter uses a more restricted definition corresponding to the finer material with which he works, the small stones and gravel having been carefully removed. The soil chemist has adopted, as mentioned above, a still more restricted definition, confined to a particular fraction of the soil, namely, that containing all the inorganic particles less than  $2\mu$ .

To an important degree, agriculture is based on clay. In fact, clay is one of the two most fundamentally important substances in soils. The movement of water within and through the soil and its availability to plants are greatly influenced by the clay content. Water appears to be held more strongly by the clay of certain soils than by that of others. It is possible that this is due in part, at least, to differences in the essential nature of the clay present. Clay also has a direct bearing on soil erosion. The state of dispersion of the clay particles and the stability of the clay aggregates greatly influence the erodibility of soils. The greater the dispersion of the clay the greater will be the susceptibility of the soil to erosion.

The adsorptive power of clay has particular importance in the field of agriculture. By virtue of this property, the loss of valuable plant nutrients especially certain of those added as fertilizers, by leaching is largely prevented. At the same time the nutrients are held by the clay in a form in which they are available to plants.

Soil clay has long been known to possess the property of base exchange : potassium, calcium, magnesium in soils generally and in arid regions, sodium, are adsorbed by clay and held in an exchangeable form. Hydrogen ions, formed in soils by ionic interchange during the growth of plants, by the decay of organic matter, and in the metabolism of micro-organisms, react with the soil replacing the adsorbed bases of the clay and thus making them available to growing plants. Thus clay constitutes a sort of storehouse for certain elements that are important as plant nutrients. Removal of basic ions by plants or in drainage water is necessarily followed by replacement from reserves. Adsorbed bases in clay may be exchanged for  $H^+$ , e.g., from  $H_2O$ .

It is only recently that soil chemists have begun to understand this substance. Modern researches on the clays have already contributed substantially to this understanding.

**The Chemical Composition of the Clay.** Chemical analyses indicate, that the four main constituents, silica, alumina, iron, and combined water make up from 90 to 98 per cent. of colloidal clay and that the colloidal matter of a soil contains a higher proportion of the important plant nutrients than does the non-colloidal fraction. This is of important practical significance and partially accounts for the fact that soils of a fine texture are considered as "strong" soils by agriculturalists.

It is seen that the composition of the clay shows a wide variation and that in all cases it differs from that of kaolin, once supposed to be the characteristic ingredient of clay. Two explanations are possible. Either the clay fraction consists of a kaolin-like mineral with excess of sesquioxides, or, in some cases, silica ; or the minerals present form a mixture of hydrated aluminosilicates and ferrosilicates of varying composition, mixed in some cases with excess of sesquioxides or silica.

Other experiments show that the clay is not similar to kaolin as it has different properties, and it is not zeolitic in nature since it can be dehydrated and then re-hydrated. In clays  $SiO_2/R_2O_3 = 1/1-5$ , whereas in kaolin this ratio is exactly  $1/2$ .

TABLE 3

*Chemical Composition of Colloidal Clay Extracted from the Surface belonging to Three Very Different Series and Obtained in Various Parts of the United States*

Constituent	Miami Series from Ind. and Mich.	Chester Series from N.J., Pa., Va. and Md.	Cecil Series from Va., N. Car., Ga. and Ala.
	Mean Percentage of 9 Samples	Mean Percentage of 15 Samples	Mean Percentage of 17 Samples
SiO <sub>2</sub> ... ..	49.78	36.47	37.50
Al <sub>2</sub> O <sub>3</sub> ... ..	25.34	31.68	36.39
Fe <sub>2</sub> O <sub>3</sub> ... ..	9.36	13.83	10.47
CaO ... ..	0.76	0.51	0.21
MgO ... ..	2.09	1.65	0.44
K <sub>2</sub> O ... ..	2.67	1.02	0.71
Na <sub>2</sub> O ... ..	0.23	0.12	0.05
TiO <sub>2</sub> ... ..	0.75	0.71	0.94
P <sub>2</sub> O <sub>5</sub> ... ..	0.29	0.42	0.21
SO <sub>3</sub> ... ..	0.20	0.28	0.13
MnO ... ..	0.20	0.33	0.12
Organic matter...	5.95	7.11	5.11
Combined water ...	8.22	12.86	13.60

**Nature of Clay Particles.** The minute and heterogeneously dispersed clay particles are electrically active, ordinarily carrying a central negative charge. This is due to an ionic double layer phenomenon. The inner layer or shell is an immovable stratum of negatively charged ions (anions) that are an integral part of the surface of the colloidal particle. The outer shell is made up of certain positive ions (cations) that are, at least in part, readily displaced. Thus as the clay particle moves through the dispersive medium, it is accompanied by a swarm of cations and the farther away the more active members of this pulsating throng maintain themselves, the greater is the electrical potential of the particle. Since the charges of the particle itself are normally negative, the particle functions much like a simple acid radical such as Cl<sup>-</sup> or SO<sub>4</sub><sup>-</sup> and will migrate to anode when subjected to an electrical current.

The outer shell of the double layer system referred to also contains a large and indefinite amount of water. Part of these water molecules are carried by the swarm of cations since all are definitely hydrated. Not only do molecules of many salts carry combined water but cations seem to have the same capacity. Na and K ions are heavily hydrated as probably are those of H ions. Moreover, water molecules are apparently packed in the interstices and channels between the plates

that make up the loosely organized clayey micelle. Even the external faces of the particle may hold water molecules by simple surface attraction.

It is now evident, however, that the mica-like clay particles are composed of two distinct parts, the insoluble nucleus, or micelle, and the outer and more or less dissociated swarm of cations with variable amounts of water of hydration. Since the cations are usually rather easily displaced, they are spoken of as exchangeable ions.

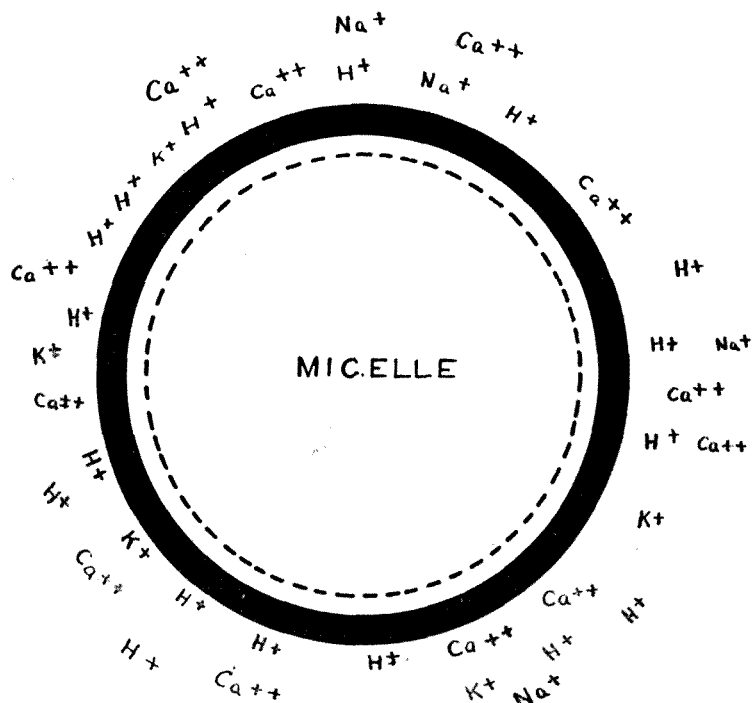


Fig. 5. Diagrammatic representation of a typical clay particle.

This replacement, called ionic exchange, or more commonly base exchange, is one of the most important of all soil phenomena. It will be considered in detail in Chapter 7.

The micelle is large relative to the cations. The order of hydration of the ion determines the thickness of the electric double layer, the more heavily hydrated ions, e.g., Na being furthest away from the micelle. This reflects the order of the lyotropic or Hoffmeister Series, i.e.,  $\text{Li}^+ - \text{Ca}^{++} - \text{Al}^{+++}$ . Since the ions furthest away are less

easily held, the heavily hydrated ones will have a low energy of adsorption and can be easily replaced, e.g., if a Na - clay is treated with a Ca salt solution, Ca will replace Na to give a Ca - clay. The reverse process would not be successful as little Ca would be replaced by Na.

It has been found that clay suspended in water exhibits dissociation in that it is apparently ionised. It is thus possible to determine the  $pH$  of clay suspensions. On filtration, however, the filtrate gives the  $pH$  value for water only. This indicates that although ionisation occurs, it is not of the ordinary type. With a H - clay dissociation of  $H^+$  ions will occur. The H - clay is thus an insoluble and yet ionisable acid and has been thus termed an acidoid. Addition of lime causes shrinkage of clay and hence flocculation, since the electric double layer will be lessened.

While all sorts of cations may thus be loosely held by the attractive power of the clay nucleus, certain ones are especially prominent. For a humid region clay, these in the order of their proportions are H and Ca first, Mg second, and K and Na third. For an unleached arid region soil the order of the proportions of the exchangeable ions is Ca and Na greatest, Mg and K next, and H least of all. The first clay is considered as having a calcium-hydrogen complex, while the second is dominated by calcium and sodium. The exchangeable cation preponderant in a colloidal clay has much to do with its physical and chemical properties. This phase is of great practical importance, and will be dealt with in Chapter 7.

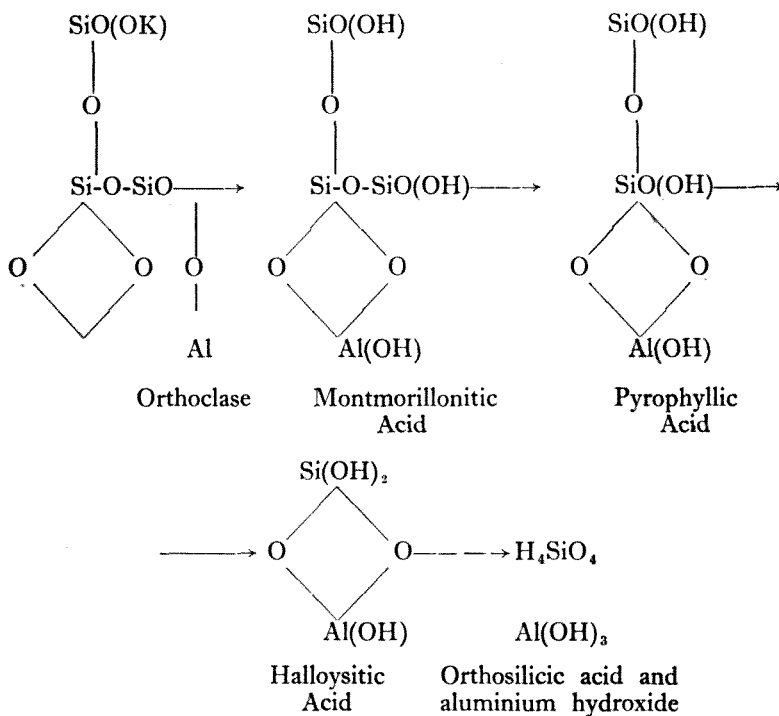
**Possible Modes of Formation of Clay.** In considering the origin of the clay complex by the chemical weathering of silicate minerals, we find that the broad effects of weathering results in the gradual hydrolysis of complex silicates with formation of hydrated silica and hydroxides of the bases. The latter are leached in the order of their solubility.

The secondary products which constitute the clay complex, may originate from silicate minerals by the removal of certain elements or groups of elements from their lattices, as by hydrolysis and subsequent leaching, the removal being accompanied in some cases by replacement with hydrogen or hydroxyl groups. The products may retain the same general lattice form, or more probably, form modified structures. (See Chapter 16.)

The origin of the clay complex may consist, as supposed by Van Bemmelen and others, in precipitation from the soluble products of

silicate hydrolysis. Whilst, according to the precipitation theory, as originally propounded, the products are absorption compounds of indefinite composition, it is equally possible that the precipitates may be definite, though complex, in composition. The difficulty in assigning formulae to the clay complex may be due either to the presence of varying proportions of relatively simple crystalline compounds, or to the complex being built up as a highly complicated lattice whose structure cannot be expressed by any simple formula.

H. G. Byers has considered the possibilities involved in the hydrolysis of orthoclase felspar, a representative of the most important group of soil-forming minerals. Assigning to it the simplest of the structural formulae proposed, the successive steps in its degradation may be pictured as follows :—



*Montmorillonitic acid* is purely hypothetical, the nearest approach to it in nature being the mineral *montmorillonite*. *Pyrophyllitic acid* is also hypothetical, differing from pyrophyllite by two molecules of water. *Halloysitic acid* corresponds with halloysite.

It is probable that both residual and precipitation products occur in the colloidal complex of ordinary soils, but there are, at present, no methods available for their exact differentiation. It is possible that residual products predominate in the weathering-complex of strongly leached soils, whilst, with incomplete or impeded leaching, and, in alluvial horizons, precipitation products predominate. The precipitation products may include, in addition to constituents deposited from solution at the seat of weathering, illuvial material transported from other horizons of the soil or from ground water.

**Isoelectric Precipitates.** Considerable light has been thrown on the constitution of the clay complex by the investigations of S. Mattson, who has studied the precipitates formed under different conditions from solutions analogous to those which might be expected to produce the colloidal complex in soils.

In Mattson's experiments, standard solutions were mixed in varying proportions and the flocculation observed immediately, and after standing overnight. In addition, the cataphoretic transport under a definite potential gradient was determined ultramicroscopically. Precipitates showing no cataphoretic transport are termed isoelectric and correspond with maximum precipitation.

By carrying out experiments in the presence of hydrochloric acid or sodium hydroxide, the effect of reaction on isoelectric precipitation of the silicates was also studied. It was shown that there is, for every  $pH$ , a corresponding isoelectric precipitate. It was also found that in the presence of bivalent cations, for example calcium, more siliceous complexes are obtained.

According to Mattson, the colloidal complex of the soil may be considered to result from mutual precipitation, at or near isoelectric conditions, from electropositive (basic) sols on the one hand and electronegative (acidic) sols on the other. Whilst it is scarcely possible that sols of opposite sign could originate simultaneously as the result of weathering, and then form isoelectric precipitates as in laboratory experiments, the isoelectric precipitate theory may serve as a useful hypothesis to explain a process in which the intermediate steps postulated by this theory are suppressed; the isoelectric precipitate presents the most stable product under the given conditions.

If we can assume with Mattson that the inorganic colloidal complex in the soil is analogous to an isoelectric precipitate, a reasonable explanation of the variation in its composition in different soil types is forthcoming. The high silica-sesquioxide ratios observed

in the colloidal complexes of arid soils and unleached limestone soils are explained by the high calcium status under such conditions. Under humid conditions the soil is subjected to leaching, whereby the protecting bases are removed. Where conditions favour the development of an acid type of organic matter, as in cool and temperate humid regions—or even, under certain circumstances, in the tropics—the most stable complex is one relatively rich in silica. On the other hand, under tropical conditions, the high temperature causes a rapid mineralization of organic residues and, although loss of bases occurs, the reaction is more nearly neutral, with the result that a complex rich in sesquioxides is produced.

Mattson's results suggest that phosphates and humic acids may form integral constituents of the colloidal complex. It is, however, not certain that the whole of the humic material of soils is thus built up with silicic acid and sesquioxides. In highly organic soils, humus may occur independently, though in intimate admixture with the clay complex. It is also possible that sesquioxides may enter into the constitution of the humus complex.

**The Clay Minerals.** Earlier writers on soils, in discussing the nature of the clay constituent, have generally assumed that it has the character of an amorphous gel, but recent work has brought into question this view of the character of clay. X-ray examinations, however, show definitely that in spite of their inconceivable smallness, the lamellar clay particles are crystalline.

A full account of the mineralogy of soil clays will be given in Chapter 16.

From the above account of the development of ideas on the clay complex, it is evident that the indefinite absorption compound hypothesis which replaced the old kaolinite hypothesis must now give place to a conception of the clay complex as consisting of a few minerals of definite crystalline structure. With them may be associated, in mixture or in loose combination, free hydrated sesquioxides. The characteristic clay minerals are secondary in character, since they do not occur in crystalline rocks, but are distinct from the zeolites, to which, however, they show certain resemblances.

**Significance of Silica-Alumina and Silica-Sesquioxide Ratios.** During recent years much attention has been given to the composition of the clay fraction as a means of characterizing soils. Significant information is given by the molecular silica : alumina ( $\text{SiO}_2/\text{Al}_2\text{O}_3$ ) or silica : sesquioxide [ $\text{SiO}_2/(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)$ ] ratio.

G. W. Robinson is strongly of opinion that the latter ratio is preferable. The use of the silica-alumina ratio implies that the ferric oxide, known to be present in the clay fraction, is uncombined with silica, and present as adventitious ferric oxide. Such an assumption cannot be made, and we are bound to assume that the clay minerals include not only aluminosilicates but also ferrosilicates, and possibly ferrisilicates.

✓ The silica-sesquioxide ratio, though of great value in distinguishing different types of clay, must not be assumed to give a complete specification of the material to which it relates. Two clays may have the same silica-sesquioxide ratio and even the same alumina-ferric oxide ratio and yet be markedly different in constitution. Complete definition can only be attained when it is possible to record all the minerals and the relative proportions of each present. In general, the silica-sesquioxide ratio of clays of humid tropical climates tends to be low, whilst that of clays of arid regions and of cold regions tends to be high.

Soils having clay fractions with silica-sesquioxide ratios greater than 2.0 are generally greyish or brownish-grey in colour in the absence of organic matter, and probably do not contain appreciable proportions of free sesquioxides, apart from illuvial accessions. On the other hand, soils with clay fractions having ratios less than 2.0 generally betoken, by their brownish, yellowish, or reddish mineral colours, the presence of free ferric hydroxide, and, by inference, aluminium hydroxide. Such soils show grey colours only under conditions favouring reduction processes.

Clays of the first class may be developed under a number of different conditions.

- (i) They may be formed by primary weathering from crystalline rocks under conditions which hinder the removal of silicic acid. This may occur under the following circumstances :—
  - (a) Leaching may be restricted owing to an excess of evaporation over rainfall as in semi-arid and arid climates.
  - (b) Drainage may be impeded, as in ground-water soils, or in soils developed from parent materials with impervious strata, such as many of the boulder clays of Northern Europe.
- (ii) They may be formed by the precipitation of dissolved silicic acid concomitantly with suspended matter in estuarine, lacustrine, and marine sediments.
- (iii) They may be formed through the removal of associated

sesquioxides from the clay complex, by leaching. This can take place in the following processes :—

(a) Podsolization under acid humus (*see* Chapter 5).

(b) Solotization, consequent on the hydrolysis of the sodium clay of alkaline soils and the removal of sodium hydroxide by leaching, whereby the clay complex becomes unstable, and looses sesquioxides. In this process, there may be an actual liberation of silica. (Chapter 13.)

Clays of the second class are formed under humid conditions in which the lowering of the base status by leaching leads to instability of the more siliceous complexes, and may even result in the partial or complete degradation or decomposition of the complex into free silicic acid and sesquioxides. These conditions obtain in all humid climates in situations with free leaching, apart from those regions where peaty humus is developed and podsolization occurs.

A. Reifenberg, from an exhaustive examination of published data on the composition of colloidal clay, has shown that the main soil groups have distinctive  $\text{SiO}_2/\text{R}_2\text{O}_3$  ratios. He gives the figures as average ones. (Table 4).

TABLE 4

Soil	$\text{SiO}_2/\text{R}_2\text{O}_3$	Soil	$\text{SiO}_2/\text{R}_2\text{O}_3$
Grey desert soils ... ..	3·62	Podsols ... ..	2·84
Red desert soils ... ..	2·08	Terra rossa ... ..	2·43
Alkali soils ... ..	3·01	Brown earths ... ..	1·98
Prairie soils and tchernozems...	3·17	Tropical red earths	1·73
		Lateritic soils ... ..	1·28

## (2) THE HYDRATED OXIDES

The second group of inorganic soil colloids are the hydrated oxides, which may be divided into the following sub-groups :—

(a) **Silicic Acid.** The occurrence of jelly-like masses of silicic acid has from time to time been reported by geologists. These range from soft gels like those prepared in the laboratory from sodium silicate and hydrochloric acid, to hard masses such as agate. They are all non-crystalline and consist chemically of silica ( $\text{SiO}_2$ ) with water and small amounts of other oxides. Their colloidal properties agree with those of the chemically prepared gels. It is often assumed

that silicic acid gel is present in soils, although there is no direct evidence of this. Very finely divided quartz is probably more common. The fact that treatment of many soils with sodium hydroxide brings silica into solution as sodium silicate does not really prove that silicic acid is present in the original soils.

(b) **Ferric Hydroxide.**  $\text{Fe}(\text{OH})_3$ . The yellow, brown or red colour of many soils suggests immediately the presence of ferric hydroxide. It is often found in the coarser fractions of soils as small nodules or concretions. These are made up of aggregates of very small crystals often held together with other brown material which cannot be recognized as crystalline. This brown material is frequently found in the silt and clay fractions and is generally assumed to be ferric hydroxide. However, there are other iron minerals which have a similar colour and which are also colloidal, so that it is difficult to be dogmatic about the occurrence of free ferric hydroxide. In certain tropical soils there is little doubt of its presence in quantity. It is certainly a more common constituent of soils than is silicic acid. When a colloidal ferric hydroxide is prepared in the laboratory it forms a reddish brown sol with very small particles. These carry a positive charge which is balanced by mobile negative ions such as chlorine in the liquid. Being positively charged the particles readily flocculate with negatively charged particles of any kind which they encounter. The ferric hydroxide gel is non-elastic and when once dried cannot readily be transformed into the sol. On long standing, sols of ferric hydroxide have been known to deposit crystals. There is evidence that the colloidal particles are plate shaped.

(c) **Aluminium Hydroxide.**  $\text{Al}(\text{OH})_3$ . It is often assumed that aluminium and iron hydroxides always occur together in soils. Actually, however, there is less evidence for the occurrence of aluminium hydroxide than for that of iron hydroxide in the soils of the temperate regions. Tropical soils which contain ferric hydroxide generally contain aluminium hydroxide as well, but whereas the ferric hydroxide is seldom crystalline, the bulk of the aluminium hydroxide can be recognized in microscopic crystals known as Gibbsite. The colloidal properties of aluminium hydroxide are very similar to those of ferric hydroxide. The particles normally carry a positive charge, but they can also be negatively charged and except for being colourless, closely resemble those of ferric hydroxide.

(d) **Other Hydrated Oxides.** There is little direct evidence of the occurrence of other insoluble hydroxides in soils.

## (3) THE PHOSPHATES

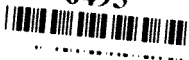
In view of the importance of the phosphates in plant nutrition it might be expected that some exact knowledge of their mode of occurrence in soils would have accumulated during their ninety years of ever-widening use as fertilizers. It is not so. The agriculturist has determined the response to phosphatic manures of every conceivable crop on every type of soil. He has encouraged the soil chemists in the invention of a multiplicity of empirical methods for the detection of phosphate deficiency in soils. And now from a prodigious mountain of literature one may cull only a few crude surmises, a mere thimbleful of facts which approach the heart of the matter.

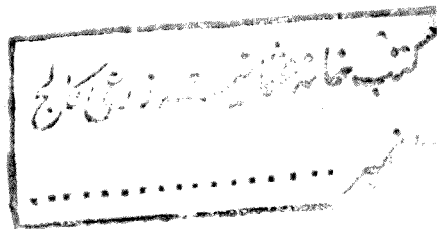
X-ray researches, however, have thrown much light on the formation of the various phosphatic compounds of the soil.

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## *Organic Soil Colloids*

IN soil formation the presence of colloidal organic matter is a sign that the biochemical processes are well begun and that biological activities are supplementing and augmenting those of a purely chemical nature. Under suitable climatic conditions life, especially bacterial and plant life, soon gains a foothold on the weathered soil materials, and, as generations pass, organic residues are left to decay and mix with the decomposing mineral mass. This admixture becomes more and more intimate as time goes on and the soil, as a natural body, exhibits its most characteristic traits only when organic matter has become an integral part of its surface layers.

Soil organic matter may be looked upon as a storehouse of important chemical elements essential for plant growth, especially of nitrogen, phosphorous, calcium, iron, manganese, and others. The utilization of some of these elements held in the inorganic fraction of the soil is also influenced by humus, through its chemical interaction with inorganic complexes.

✓ **The Complex Nature of Humus.** The word humus, like the word clay, is used in different senses by different individuals. To most farmers it represents, somewhat vaguely, the sum total of all that organic matter in the soil which has lost its original cellular structure. The chemists work with a more restricted definition. They would exclude from consideration all partly-decomposed plant residues and all micro-organisms. Chemists often use the term "humic matter" rather than "humus" in order to make it clear that they mean only the black colloidal matter which accumulates in the soil as a result of the decomposition of plant and animal remains. Humic matter occurs naturally in two forms. In the one it is a mixture of colloidal acids and this form is characteristic of high-moor peats and of sour soils generally. In the other it is present as the calcium salts of these acids and in this form predominates in fen soils,

in calcareous soils and in fertile mineral soils with a neutral or slightly alkaline reaction. Intermediate types are present in soils of slight acidity.

During the time of Liebig, humus was regarded as the chief plant food, and the earlier chemists carried out their investigations with a very full consciousness of its importance. The great Berzelius himself helped to establish two major facts ; firstly, that humus is a mixture, and secondly, that it is chiefly a mixture of organic acids or of salts of these acids. The acceptance of Liebig's views on plant nutrition diverted the attention of soil chemists from the study of humus, whilst its colloidal character, first clearly recognized by van Bemmelen in 1888, kept at bay the organic chemists who threw themselves so whole-heartedly into the elucidation of the chemistry of natural products like the sugars, the terpenes and even the proteins during the latter part of the nineteenth century. More recently, the question as to the chemical constitution of the acids of humus has been investigated by fuel chemists. The reason for this development lies in their conviction that humus, as typified by peat, represents the first stage in the formation of coal. Many of their experiments and conclusions are directly applicable to the problem of the constitution of humus in the soil.

Humus as a whole can not be separated from the soil like the sand or the clay. It can be destroyed by igniting the soil, when the black colour disappears and the reddish mass left is quite different from the original soil. The heat, however, has rather a drastic action and affects the mineral as well as the organic part of the soil. A gentler method of removing the humus is to oxidise it with hydrogen peroxide.

Part of the humus, however, can be extracted by means of dilute alkalis. Shake 100 gm. of soil with 500 c.c. of 5 per cent. hydrochloric acid, allow to settle, pour off through a filter, and wash with water. Then transfer the soil to a bottle, add 500 c.c. of 5 per cent. caustic soda solution, shake, and leave for some hours lying on its side so that as large a surface as possible is exposed to the alkali : shake periodically. Before long the alkali becomes dark coloured. Again allow to settle and siphon off, if you can, filter on a Buchner funnel by the aid of a pump : this is rather a slow process. To the clear dark-coloured filtrate add some strong hydrochloric acid drop by drop till the liquid is just acid. A dark brown precipitate is thrown down containing part of the organic matter. On drying, this shrinks very much

to little lumps almost black in colour which readily burn and leave behind a little red ash. Its composition varies considerably, but after it is thoroughly dried in a steam oven it usually contains about 50-57 per cent. of carbon, 35 per cent. of oxygen, and 3-8 per cent. of nitrogen.

**Determination of Soil Organic Matter.** Owing to the great importance of the organic matter, chemists have made many attempts to determine how much is present in the soil. Advantage is taken of the fact that organic matter burns away while mineral matter does not : hence some of the soil is burnt, and the loss of weight is measured. This method is simple, but unfortunately it is not quite sound, for the loss of weight includes some of the water that is very firmly held and also carbon dioxide and other substances given off by some of the mineral matter.

A better method of discovering how much organic matter there is in the soil is to determine, by a combustion method, the percentage of carbon present. (The total amount of organic matter in the soil is estimated approximately by multiplying the total carbon content of the soil by the factor 1.724, corresponding to an average carbon content of 58 per cent. in soil organic matter.)

The study of the humified (i.e., organic residues sufficiently decayed to have lost its usual structure) part of the soil organic matter is very difficult because it has not yet been possible to separate it in its original form from the non-humified fraction and from the inorganic part of the soil. Solvents ( $\text{NH}_4\text{OH}$ ,  $\text{NaOH}$ ,  $\text{Na}_2\text{CO}_3$  and pyridine) which are supposed to dissolve the humified organic matter or acetylbromide, which dissolves natural plant material, but leaves the so-called "humus" complexes in the soil intact, have been used by various workers for estimating the humus content of the soil.

Waksman and his co-workers, however, rejected all these methods as unsuitable and recently proposed a new one by which we may determine the approximate chemical composition of the bulk of the soil organic matter. It may be noted also that Gedroiz and Vernander and Sokolowsky have suggested a method by which the soil is treated with neutral  $\text{NaCl}$  solution until the total humus is saturated with  $\text{Na}$ , the  $\text{NaCl}$  in the extract being then separated by dialysis from the dispersed humus. Though this method takes too long to make it convenient for analytical estimation it separates the supposed "humus" in a neutral solution, avoiding all chemical interchange during the separation.

It should be noted that the humus content of the soil whether field, orchard or garden is considerably greater than the total amount of organic matter present in the crops grown on the soil in a given year.

✓ **Origin of Soil Humus.** We should now enquire into the general nature of the soil organic matter. If we take a spadeful of soil, we shall at once notice recognizable plant remains, fragments of roots, stems, and perhaps also leaves. We shall also by minute search discover seeds. But if we collected together all these plant remains, we should still find that the bulk of the organic matter present remained unaccounted for. (As much as nine-tenths of the soil organic matter may consist of humus) This is the characteristic organic matter of the soil. It occurs associated in intimate mixture or even in loose chemical combination with the clay, forming the clay-humus complex, or colloidal complex of the soil.

Soil humus is formed by the alteration or partial decomposition of organic matter added to the soil. Under natural conditions this means the decomposition of the remains of plants that have grown in the soil, or remains of animal life or excreta. In cultivated soils, we have as additional sources of humus, organic manures, of which the principal is farmyard manure; and farmyard manure consists mainly of the decomposed excreta of animals, mixed with the litter, usually straw, used in their bedding.

✓ **C/N Ratio.** Plant remains for the most part, consist of the fibrous constituents of plants, and are poor in nitrogenous compounds, starches, and sugars. In passing, we may note that owing to their poverty in nitrogen, the ratio of carbon to nitrogen, the so-called C/N ratio, is very high, something of the order of 40 or more. The organic matter of most soils contains carbon and nitrogen in the approximate ratio of 10-12 : 1. Assuming that this organic matter contains an average of 55 per cent. of carbon and 5.5 per cent. of hydrogen and 5.5 per cent. of nitrogen, then, if the nitrogenous portion be assumed to be of a protein character, it would amount to  $5.5 \times 6.25 = 34.4\%$ , or a little over one-third of the total organic matter. There is, however, a distinction between the supposed protein of soil organic matter and that present in the plant, for whilst the latter, on being added to the soil, undergoes a rapid decomposition, the soil protein appears to be highly resistant to micro-biological action, although it may be partially hydrolysed by dilute acids and decomposed by hydrogen peroxide.

**The Composition of Plant Tissue.** (About 75 per cent. or even more of average green plant tissue is water.) The dry substance is made up of carbon, oxygen, hydrogen, nitrogen, and mineral matter (see Fig. 6). Although over 90 per cent. of the dry matter is carbon,

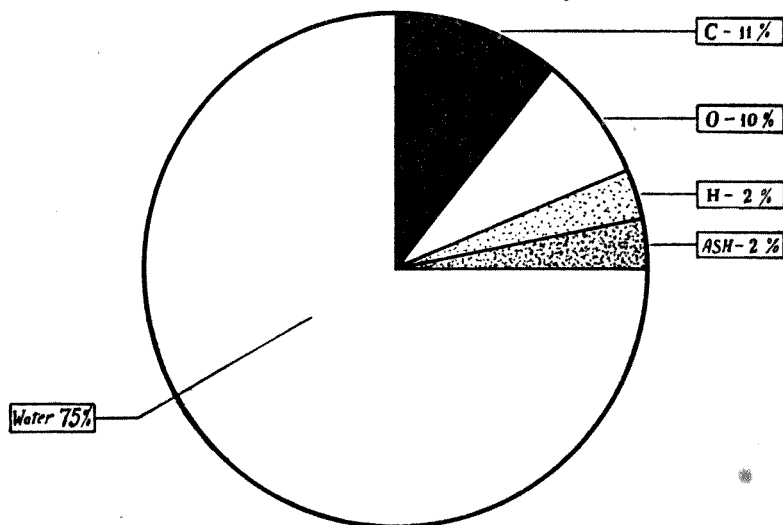


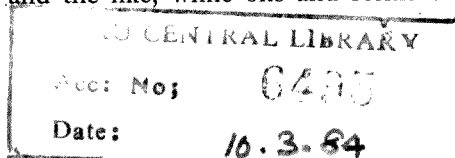
Fig. 6. Diagram showing the generalized composition of green plant tissue. The nitrogen is included in the ash. (After Stoddard.)

oxygen, and hydrogen, the other elements play a vital role in plant nutrition and are important additions to the soil when the organic residues become a part thereof. Nitrogen, sulphur, phosphorus and calcium from organic sources are particularly important. In fact, a very large proportion of the soil nitrogen is normally present in this form.

The actual compounds in plant tissue are many and varied. For convenience they may be classified very simply under four heads :

- (1) Carbohydrates.
- (2) Oils, waxes, and resins.
- (3) Organic acids and their salts.
- (4) Nitrogenous compounds. )

The mineral constituents of plants, exist mostly as salts of organic acids, becoming evident when the organic matter is ignited. The carbohydrates include such readily decomposable compounds as starch and sugars and more stable substances such as the various celluloses and lignin. The fats are represented by the glycerides of butyric, stearic, oleic, and the like, while oils and resins of many



kinds, simple and complex, are associated with them. All plants contain organic acids and their salts, often in considerable amounts.

**The Composition of Soil Organic Matter.** The nature and constitution of soil organic matter has long presented a difficult problem for soil chemists. Its complexity was recognized at an early stage by the first workers in the subject. One of the chief difficulties in investigating the problem is the impossibility of isolating the organic matter of ordinary soils from its accompanying mineral matter as above mentioned. It was inevitable, therefore, that much of the earlier work was carried out on peats, consisting wholly or mainly of organic matter. And since the mode of origin of such organic matter is different from that in the majority of ordinary soils, it is probable that the results obtained are only of limited applications.

G. W. Robinson and J. O. Jones suggested a simple fractionation of soil organic matter into humified and non-humified by the use of boiling 6 per cent. hydrogen peroxide as a reagent. The assumption underlying this method of determining the degree of humification was, however, questioned by W. O. Robinson, who showed that, in the presence of soil, cellulose is appreciably attacked by 6 per cent. hydrogen peroxide. The peroxide method for determining the degree of humification of soil organic matter has, however, found a certain application in the study of forest soils.

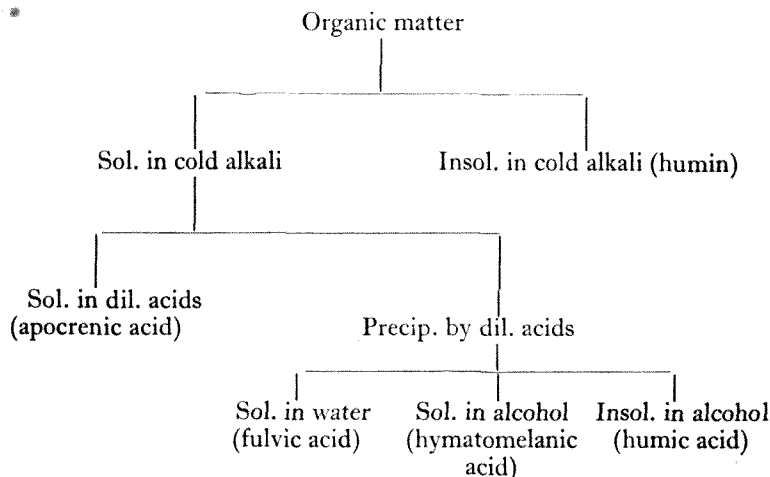
A humus has however, been synthesized from glucose and glycine by V. A. Beckley with a nitrogen retention similar to that of natural humus. During synthesis from glucose and glycine, a furfural ( $C_5H_4O_2$ ) compound was produced which was also detected in soil humus and rotting manure. On exposure to air and sun a humus-like compound was formed. It is suggested that this furfural compound is an intermediate product in humus formation.

Some of these furfural compounds which have been isolated by Schreiner and Shorey and others from soils may be common constituents of the majority of soils. Others are certainly more characteristic of the particular soils examined. It is difficult to say what significance is attached to these compounds, although one or two have been shown to have a definite effect upon the plant.

The humus fraction varies in its ultimate composition but analyses of the fraction obtained from various soils are all of the same order. Round figures approximating to the average composition are

C=50%, O=35%, N=5%, H=5%, Ash=5%.

✓ **Fractionation of Soil Organic Matter.** A possible fractionation of soil organic matter is shown in the following scheme :—



We may now consider the conditions under which the four fractions of soil humic matter may enter and leave the colloidal realm.

I. *The fulvic acid fraction* is soluble in water, giving a yellow or brown solution which passes the usual ultra-filters. The colour darkens when the soluble sodium, potassium or ammonium salts are formed. The formation of the calcium or magnesium salts causes precipitation and, so far as we can judge from the scanty data, these salts do not readily peptize to form stable sols.

II. *The hymatomelanic acid fraction* is insoluble in water but soluble in alcohol. Stable sols of this acid in water can be prepared in two ways ; either by pouring the alcoholic solution into a large volume of water or by dissolving the precipitates in alkali and precipitating by means of a mineral acid and then washing out the added free acid and the salt produced, by distilled water. When the concentration of mineral acid has been sufficiently reduced, the hymatomelanic acid peptizes to give a stable brown sol similar in appearance to that prepared by the first method. The sodium and potassium salts of hymatomelanic acid are soluble in water but insoluble in alcohol. The calcium and magnesium salts are insoluble both in water and in alcohol. Hymatomelanic acid, with an equivalent weight of about 200 has a very high base exchange capacity.

III. *The humic acid fraction* is insoluble in water and in alcohol. It very readily passes into the sol by peptization when the precipitate obtained by adding an acid to sodium humate solution is washed with distilled water. To a slight extent it also peptizes in alcohol, so that the humatomelanic acid fraction generally contains some colloidal humic acid which can be removed by an ultra-filter. The sodium, potassium and ammonium salts are soluble in water, the calcium and magnesium salts being insoluble and not easily dispersed when once precipitated. Its equivalent weight is about 300-350, and its base exchange capacity, though high, is lower than that of humatomelanic acid.

The chemical investigation of the humic acid fraction has proceeded along two main lines. In studying its chemical reactions the classical methods of the organic chemists have been beset with such difficulties that argument by analogy has all too often been invoked. Thus the natural occurring humic acid has been compared and identified at different times with a whole series of artificial products which can easily be prepared in the laboratory, and which have, so far as outward appearance goes, the same general properties. We now know that none of these is identical with the naturally occurring humic acid, with the possible exception of that from lignin. The second line of attack has been more direct, and so far as soil humic acid is concerned, more successful. Something may be learned from the elementary composition of humic acids, particularly when the figures are placed alongside those of the plant materials which are the parents of humic matter.

The constitution of humic acid, as judged by X-ray diagrams is analogous to that of high-polymer compounds. By electronographic analysis, I. D. Sedelestky brought evidence indicating a crystalline structure of humic acid. On the basis of a critical examination and evaluation of X-ray diagrams of natural and artificial humic substances from various sources, he also came to the conclusion that regardless of the origin of such substances their basic structure must be aromatic (graphite lattice).

G. Gemmerling found that humic acids from different soils are not identical, but there is a crystalline component which does not vary much from soil to soil. S. Vladichemisky showed that humic acid from a mountain peat soil showed a high capacity for the formation of a crystalline structure and for fixing water. Chernozem humic acids showed these properties in lesser degree and in general behaved more like hydrophobic than hydrophilic colloids.

A theory has been put forward recently by C. Enders that humic acid is formed by the condensation of amino-compounds with methyl glyoxal produced from carbohydrates. Lignin is apparently supposed to be formed in an analogous way.

The coagulation of sols of humic acid and of calcium humate closely resembles that of clay sols in its general features. The sensitivity of humic acid towards coagulating agents is, however, considerably less than that of the clays, and calcium humate is rather less sensitive than humic acid.

The absorption of humic acid and of the soluble humates at surfaces is strong. This adhesion, together with their small sensitivity towards coagulating agents, causes humic acid and the humates to act as protective colloids. In this respect they are to be regarded as comparable with gelatin, starch, etc. It has been shown that one gram of colloidal clay may be completely protected by 10-20 milligrams of colloidal humic acid up to the point at which humic acid itself coagulated. Now humic acid is coagulated by amounts of electrolyte which are seldom more than ten times those required for clay. Thus the effectiveness of humic acid and the humates as protective colloids is displayed over a much narrower range than that of gelatin. Nevertheless, it is of great importance in soils and the subject is worthy of much closer study than it has yet received.

When water is removed from flocculated humic acid or from calcium humate a point is soon reached at which a black, non-elastic gel is formed. This shrinks enormously on drying and eventually becomes a brittle solid. The process resembles the drying of silicic acid gel, and the brittle black humic acid, like dried silicic acid, does not pass back again into the sol form when water is added. While the gel is still soft and moist it readily expands to its original volume on addition of water and eventually peptizes to give a sol. The contraction and expansion of peat under natural conditions is a very well-known fact. In dry weather great cracks and fissures appear, accompanied by a drop in the surface level. As the peat bed once again becomes saturated with water the original condition is restored. It is seldom that peat beds become so dried out that the irreversible stage is reached, but there is a strong probability that the humus in the surface layer of certain cultivated soils in dry regions will actually attain it.

IV. *The humin fraction* resembles colloidal clay, it never goes into true solution, and, so far as it is known, it only gives stable sols

when sodium, potassium or ammonium are the exchangeable cations present. For this reason it has so far proved impossible to separate it from clay, and it can only be studied in a reasonably pure state when prepared from sandy soils or from peats. Very little is known about this fraction, but it is probable that its base exchange capacity lies between that of the humic acid fraction and that of the clays.

Most of the colloidal-chemical researches on the properties of humic matter have been carried out, however, on the crude mixture of the humatomelanic and humic acid fractions which is obtained by acidifying an alkaline solution from peat. No quantitative studies have been made to determine how far the properties of soil humic matter, with its much greater nitrogen content, agree with those of peat humic matter.

#### MODERN THEORIES OF HUMUS FORMATION

**Waksman's Theory.** The fundamental idea of Waksman's theory is the hypothesis that the bulk of humus-forming materials originate not from the whole organic matter of the soil, but from the lignin and protein. The average chemical composition of the organic matter of six soils according to Waksman's analyses gave 43.27 per cent. lignin ("lignin-humus-complex" or "soil lignin"), 33.81 per cent. protein or organic nitrogenous complexes, 11.02 per cent. water-insoluble carbohydrates (cellulose, hemicelluloses, etc.), and 2.77 per cent. ether and alcohol-soluble substances; thus 78.08 per cent. was made up of two complexes; namely the protein and the lignin. The same is true of low moor and sedimentary peats and of well decomposed manure. It is thus concluded that the humus of mineral soils, of well-decomposed peats, and of composts, consists predominantly of two chemical complexes, namely the lignin and proteins, with an admixture of other substances such as fats and waxes, cellulose and hemicelluloses, organic acids and alcohols; the nature and abundance of these accompanying substances depend upon the nature of the plant and animal residues added to the soil or used in making the compost, upon the extent of the decomposition, and upon the conditions under which this decomposition takes place, such as reaction, moisture content, aeration, and temperature. Whether the two major complexes, namely the lignins and proteins, form one chemical complex in humus or whether they exist independently, still remains to be determined.

The experiments made by Waksman and Iyer show, however,

that the lignin exercises a depressive effect upon the decomposition of proteins in pure and mixed cultures of micro-organisms, not owing to any toxic action of the lignin, but on account of a chemical interaction between the lignin and protein molecules. This is the fundamental idea of Waksman's humus theory.

Two important facts about humus were established a few years ago at Rothamsted. First, the nitrogen in humus is in a protein combination and second, the rate at which humus is formed from plant material is approximately proportional to the loss of lignin but bears no relation to the loss of any other plant constituent. This indicates that lignin (formed from cellulose in the cells of plants during growth) and protein contribute to the chemical structure of humus. There are, however, several reasons for thinking that humus is not likely to be a mere mixture of lignin and protein. For example, proteins are easily attacked by micro-organisms while humus obviously is not. But it is found that if lignin and protein are very intimately mixed, and more if they are heated together and still more if they are mutually precipitated, the protein part of the combination is less susceptible to bacterial attack.

**The Lignin-Derived Fraction of Soil Organic Matter.** Very considerable advances have been made in the chemistry of lignin in the past decade mostly because new methods of extraction have been devised. As a result there is a wealth of information as to the reactions of lignin that should be carried over and applied to soil organic matter or extensively decomposed plant residues, in an attempt to determine the nature of the groupings present and the extent of the modification undergone.

It is now perfectly certain that there is not one lignin but many lignins, just as there is not one protein but many proteins. The general structural pattern may be the same but they may differ in degree of polymerization, and to some extent in constituent groupings. Clear differences are recognizable between the lignins of deciduous and coniferous woods. The lignin-derived fraction of soil organic matter may well differ according to the source, and it is not necessarily to be expected that the organic matter of a grey-brown podzolic soil for example will be the same as that of adjacent prairie soils even though substantially the same microbiological transformations may go in both soils. There may be, however, a greater measure of similarity between hardwood lignin and that of grass roots, than between hardwood and softwood lignins. However, the

opinion is now held quite generally that lignin or lignin-derived material contributes substantially to the organic fraction of soils.

**The Organic Nitrogen Fraction of Soils.** At least as important as the lignin-derived fractions of soil organic matter are the nitrogenous complexes, which are presumably mostly, if not exclusively, of microbial origin. One of the most fascinating and challenging problems that confronts the soil chemist is the nature of these complexes and the factors controlling their availability. The organic nitrogen of the soil is a much neglected field. All through the "humic-acid" era much effort was expended in the attempt to get nitrogen-free preparations. Nitrogen was regarded as an impurity and not a part of the true humus, instead of as a characteristic major fraction to which, from the fertility standpoint, much attention should be given. Agriculture is largely dependent on the steady release of the soil nitrogen in the form of nitrate at such a slow rate that only a few pounds per acre may be present at any time. Nitrate is a fugitive commodity under humid conditions. It must be admitted, however, that we have quite unsatisfactory information as to the factors controlling this slow release from the reserve supply, which in prairie soils may amount to several tons per acre. The process can be "explained" on a biological basis (*see* Chapter 6), but the explanation again is a matter of experience rather than real enlightenment. Actually there is a considerable amount of organic nitrogen of microbial origin which is probably relatively uniform in composition. The distribution of amide, mono-amino, and di-amino nitrogen in this type of soil organic matter is such as to indicate that it is proteinaceous, or, since not all the nitrogen can be accounted for, at least protein-derived. This organic nitrogen is either inherently very resistant biologically (which is unlikely), or in some way made unavailable, so that not much over 1 per cent. becomes available in any one season.

**Stabilization of Nitrogen by Lignin.** Waksman has put forward the theory that the availability of the protein is reduced through combination with lignin, as we mentioned before, and has supported this by interesting experiments on the properties of precipitated mixtures of lignin and proteins. The availability of the protein in these ligno-protein complexes was much reduced in soil and solution culture.

**Stabilization of Nitrogen by Clay Minerals.** An alternative explanation of the unavailability of the organic nitrogen of the soil,

does not, however, involve lignin at all. This is the theory put forward by Gieseking who has demonstrated that mixtures of proteins with certain clay minerals are far less easily hydrolyzed by proteolytic enzymes than are the proteins alone. The active minerals are those with an expanding lattice (*see* Chapter 16.)

**Interaction of Organic and Inorganic Soil Colloids.**

Whether or not there is a clear-cut clay-protein complex in soil, interaction between the inorganic and organic colloids of the soil is highly probable. Surface-active materials with cationic and base-retaining properties present together and bathed by a water film are hardly likely to be inert with respect to each other. That some of the colloid is microbial-derived, some plant-derived and some of mineral origin is no bar to its activity. If the environmental conditions are such that some movement of dispersible or soluble organic matter occurs there is a possibility that the whole of the clay colloid is covered to some degree with a mantle of organic matter retained by a variety of forces, some weak, some strong. Perhaps the word "fabric" which Kubienska used in speaking of soil correctly describes the knitting together of organic and inorganic colloids. Several interesting papers on this subject have appeared recently.

Springer believes that the organic and inorganic constituents of chernozems are so closely united that the complex is extremely stable. In Tyullin's opinion the easily peptizable electro-negative colloids which are primarily organic and responsible for high fertility, are adsorbed on the surface of the organic-mineral gels, whereas the fraction not easily dispersed is firmly retained within the gel in an inactive form. Accordingly Meyer suggests that the formation of natural organo-clay complexes takes place when the latter are being formed by the weathering of primary minerals into montmorillonitic or micaceous colloids, and not by combination with pre-existing clay.

### CONCLUSION.

Looking over the chemical studies on soil organic matter, one cannot help being struck by the fact that so few workers have attacked the problem on a strictly chemical basis, like that, for example, of adsorption and the isolation and determination of structure of vitamins or hormones in recent years. It is true that in such cases there has been present a physiological entity that could be assayed biologically for purity but even so the task has often been

formidable. A survey of the literature leaves the impression that many of the investigations of soil organic matter were undertaken to provide support for a theory of the mode of formation of humus and this fact from the beginning prejudiced the results.

In the past, far more people have worked on the clay colloids than on the organic colloids of soil, yet the problems of the latter that await solution are no less fundamental than those of the former and as full of possibilities for the better understanding of the soil in relation to plant growth.

Consider the advances that have been made in the past two decades in our knowledge of the separation, structure, and properties of the clay minerals, and how this knowledge has illuminated the obscurity of various soil phenomena that impinge directly on day-by-day problems of fertility, such as base exchange or phosphate fixation. The chemistry of soil organic matter is in a position analogous to that of the clay fraction when all the information that was possessed about it was the content of its various sesquioxides.

## *Biochemical Processes in Soils and Soil Organic Matter*

THE fundamental characteristic of soil is its productivity ; that is, its capacity to produce green plants. The plants, during a period of their growth, absorb and accumulate a certain amount of the radiant energy of sunlight and convert it into a form available to other living organisms, which are incapable of utilizing the energy of the sunlight directly.

In the soil organic matter is decomposed into simple compounds of its constituent elements. Various complicated biochemical reactions are involved in this process and energy is liberated. A great variety of organisms are responsible for bringing about these reactions.

The diversity of these organisms and the interaction of one group upon another has of recent years received much attention in particular by the Rothamsted workers in England and by Waksman and his colleagues in the United States. The investigations, however, are beset with enormous difficulties and a large part of the work so far done has been in the development of suitable technique.

The microbial population of the soil consists of bacteria, fungi, actinomycetes, algae and protozoa. No accurate figures can be given of its total numbers, but some idea may be formed by the average estimate of ten to twenty millions of bacteria per gram of soil.

The micro ~~forms~~<sup>organisms</sup> may be divided into two groups : heterotrophic organisms, which, like animals, require an external supply of organic matter to provide their energy and the material for their increase and autotrophic organisms which, like plants, are able to synthesize their bodies from carbon dioxide and simple inorganic salts. This division is not a hard and fast division of the organisms, since under a different set of conditions some autotrophic organisms can behave heterotrophically—e.g., certain species of Algae which in the absence of light lose their chlorophyll and function as saprophytes.

**Functions of the Heterotrophic Organisms.** These form the bulk of the soil population, the function of which is to break down organic matter into simple substances available for plant nutrition or for further synthesis by micro-organisms acting autotrophically.

Not much is known of the many changes whose sequence comprises this decomposition of proteins, carbohydrates, and other organic constituents of plants, but two main types of the decomposition which may be labelled direct and indirect are recognized.

In the direct decomposition of soil organic matter the decomposition of some part of the non-nitrogenous constituents and of a large part of the protein proceeds steadily and "normally" to the formation of carbon dioxide, water, ammonia, and such simple and "final" products of organic disintegration and involves the intermediate production of organic acids. The economic functions of the process of decomposition are the production of simple organic nitrogenous compounds and the maintenance of the important microbial life of the soil.

The main functions, then, of the great bulk of heterotrophic organisms is the oxidation of organic matter, in which process oxygen is taken up and carbon dioxide is formed. The amount of oxygen taken up and the amount of carbon dioxide formed may be estimated and taken as a rough measure of the bio-chemical activity of the soil. Now, the bio-chemical activity of the soils is intimately associated with fertility and the amounts of oxygen absorbed and of carbon dioxide liberated may therefore give some index of fertility on soils of the same type which are similarly situated. In one series of such soils it has been shown by Russell that the order of the amounts of oxygen taken up in a given time under fixed conditions is also the order of productiveness.

Russell computes that the amount of oxygen absorbed by the farmyard manure plot in Broadbalk Field at Rothamsted is of the order of 2 litres per square metre per day. Average arable land will probably absorb somewhat less than this.

A considerable number of the heterotrophic organisms which under normal conditions use organic compounds as their source of nitrogen, use nitrate when there is a preponderance of non-nitrogenous organic matter in the soil. This action is stimulated by a plentiful supply of such easily oxidizable carbohydrates as starch, sugar, or unrotted straw.

Other heterotrophs (e.g., *B. denitrificans*) will, under anaerobic

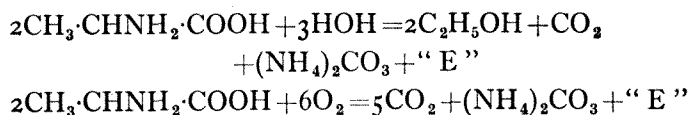
conditions, reduce nitrate to free nitrogen, and others will reduce sulphate to sulphuretted hydrogen and free sulphur.

In marked contrast to the general disintegrating action of the heterotrophic organisms as a whole, we have the important group which synthesize their protein material from free nitrogen and thus provide a valuable source of nitrogen, which in its turn eventually becomes available for plant nutrition. The bacteria (*Azotobacter*, *Clostridium* and *B. radicum*) are the main agents in this process.

The autotrophic organisms which synthesize their own organic matter generally have highly specialized functions. Important among them are *Nitrosomonas* which oxidize ammonia to nitrate, sulphur bacteria which oxidize sulphur and hydrogen sulphide to sulphate, and the iron bacteria which accumulate ferric hydroxide in their sheaths. All these transformations are carried out through enzymic action. Enzymes are organic catalysts, crystalline, colloidal, and more or less specific in their ability to hasten chemical change. Considering the tremendous effect of only small numbers of organisms, enzymic action must be extremely powerful and effective.

The three most important enzymic transformations that occur in soils are hydrolysis, oxidation, and synthesis. They take place concurrently.

When amino-acids are subjected to the influence of soil organisms, the simplification may be one of hydrolysis or oxidation or both. The following reactions are merely suggestive in general of what takes place. Alanine is the amino-acid used in the illustrations.



The organisms obtain energy and tissue-building materials from the transformations, leaving as by-products certain simple compounds. The change of the ammonium carbonate to nitrates (nitrification) by certain special-purpose bacteria is another example of oxidation.

The building up of elements and simple compounds into complicated tissue material by the micro-organisms is designated as synthesis. It takes place continually. Nitrates, ammonium, elemental nitrogen, amino-acids, carbon dioxide, oxygen, and other substances are so utilized.

### THE RESULTS OF THE BIOCHEMICAL ACTIVITIES OF SOIL ORGANISMS.

The smaller organisms attack organic matter in the soil in order to obtain energy and nutrients for satisfying their own needs for multiplication. Multiplication or the maintenance of its own kind on the earth is the one aim and purpose of all life in nature. Soil organisms, being no exception, work solely for their own benefit and not for that of crop plants or of man.

Crop plants and man are aided indirectly as a consequence of the ability of the higher plants to utilize some of the products of the decomposition of plant materials into simple substances by soil organisms.

The organisms bring about the decay of the organic matter that they find in the soil for the purpose of obtaining energy and nutrients from it. One group of organisms performs one step in the long process of simplification or decay of organic matter, another group takes the next step, and others in turn carry on from where their predecessors left off until the task of reduction is completed. In addition to reduction the building up, or synthesis, of organic matter is brought about by soil organisms in their own growth.

Among the essential products of the work of the organisms are ammonium compounds, nitrates, carbon dioxide, and sulphates. Carbon dioxide supplies carbon for the autotrophic forms and produces carbonic acid,  $H_2CO_3$ , that most essential acid in the liberation of plants nutrients from the mineral part of the soil.

The steps, then, in the process of the simplification of nitrogen are decay, ammonification, and the formation of nitrites and nitrates. Though plants use nitrogen in the form of nitrate and ammonium compounds and probably others as well, the ordinary field and vegetable crops on well-drained and well-aerated soils take up much of their supply of nitrogen in the nitrate form.

The rendering available of these compounds of nitrogen, and indirectly of the other nutrients of the soil, to the higher plants must be considered as the essential beneficial activities of the smaller soil organisms. Many of the chemical reactions that take place in soils are the indirect result of the work of these organisms. This work is essential because our crop plants cannot use farm manure, green manures, or crop remains directly. These organic materials must first be changed to the forms that plants can use for growth. Again, plants cannot entirely feed directly upon the sand, silt, or clay

particles that constitute much of the mineral part of soils. This material must first be acted upon, in part at least, by the products of the work of soil organisms. It seems clear, therefore, that all higher plants, and consequently the higher animals and man as well are dependent on these lowly forms of plant and animal life, collectively referred to as soil organisms.

### PRODUCTS OF THE DECOMPOSITION OF ORGANIC MATTER

Chemically soil organic matter represents a mixture of a great many different substances which can be classified into three groups :

- (1) Carbohydrates.
- (2) Protein.
- (3) Fats, resins, waxes and similar compounds.

The gradual decomposition of these organic substances into the most simple mineral compounds is spoken of as mineralization. The ultimate end-products of mineralization are principally water and carbon dioxide and smaller amounts of free nitrogen, ammonia, methane, etc., and a few simple mineral salts. The process of mineralization, or reduction of the fresh residues to the simple end products, proceeds gradually with the formation of a number of intermediate substances. Some of these are products of the decomposition of the original material, and others are the result of resynthesis. Sooner or later the entire amount of organic residues turned over to the soil in any given time undergoes complete mineralization.

The aerial portions of plants under normal conditions are covered with a varied mixture of micro-organisms. When the plants die, are cut down, or are ploughed under, this varied population, already in intimate contact with them, is ready to begin the progressive biochemical processes that transform plant and animal remains into carbon dioxide, ammonia, and minerals. Plant residues at the beginning of the decomposition process contain sugars, starches, hemicelluloses, celluloses, lignins, proteins, and fatty or waxy substances in percentages specific to their origin. Under favourable temperature and moisture conditions, the micro-organisms present on the material or in the soil quickly increase to fabulous numbers.

The decay of fresh organic materials in the soil may thus be regarded as occurring in four more or less distinct but orderly steps :

- (1) The starches, sugars, and water-soluble proteins are the first to be attacked and broken down by the organisms in the soil.

- (2) Next follows crude protein, pentosans, and hemicellulose.
- (3) Cellulose appears to be more resistant but still yields readily to the action of the organism.
- (4) Decomposition of the oils, fats, waxes, resins, and lignin is very slow.

These latter materials, especially lignin, contribute largely to the production of humus.

Of the carbonaceous part of organic matter, carbon dioxide,  $\text{CO}_2$ , and water,  $\text{H}_2\text{O}$ , are the end products. The nitrogen-carrying part, the proteins, are changed to amino acids, to ammonia, and finally to nitrites and nitrates.

Immediately after fresh organic matter, such as farm or green manures, is mixed with the moist warm soil, active decay becomes intense and results in the liberation of large quantities of carbon dioxide. This takes place simultaneously with a sudden and enormous increase in the numbers of the various soil organisms which are bringing about these changes. When the supply of fresh organic matter has been reduced, the numbers of organisms and the evolution of carbon dioxide dwindle simultaneously because the organisms have used up the more readily decomposable carbonaceous part of the plant tissues. Some of the more resistant materials, such as oils, fats, resins, and lignins, remain in the soil much longer.

Considering the decomposition of plant residues as a whole we may distinguish two main types, namely, (a) oxidation and (b) humification.

(a) **Oxidation** has the same result as combustion in oxygen. The organic matter becomes oxidized to carbon dioxide and water, and is, therefore, completely lost from the soil. The carbon dioxide, which may form up to 1 per cent. or more of the soil air, comes mainly from the biological oxidation of organic matter. Indeed, the carbon dioxide thus formed is the most important source of the atmospheric carbon dioxide that is utilized by plants in carbon assimilation. Oxidation is essentially destructive, and where this type of decomposition predominates, added organic matter rapidly disappears from the soil. It is favoured by moisture, warmth, and, above all, by aeration. It is remarkable how quickly organic matter can disappear from soils when conditions favourable for oxidation obtain, as, for example, in cultivated soils in the tropics. Even in temperate climate, cultivation, by causing aeration, favours loss of organic matter. As mentioned above the bulk of the humus is much less

rapidly decomposed than are recent plant remains. This is fortunate, because if it were as readily oxidised as these residues, organic matter would speedily be lost, with a host of undesirable consequences for plant growth.

(b) **Humification.** Whilst oxidation is destructive of organic matter, the processes of the other type, namely, humification, are conservative in their effect. By these processes, plant residues become changed into the dark-coloured amorphous material, humus, which forms the greater part of the organic matter of soils. There are a number of different processes of humification, not always as clearly distinguished as they should be.

(1) *Anaerobic humification.* The commonest form of humification is the so-called anaerobic humification, i.e., the humification that takes place with absence or restricted supply of oxygen. Such conditions obtain where plants residues decompose under water, as in pond or lake mud. They also obtain in soils that are waterlogged. But even in well-drained soils there are periods when high moisture content results in anaerobic conditions occurring within the soil crumbs.

Whilst, in anaerobic humification, a certain loss of organic matter occurs as gaseous products, carbon dioxide, methane, etc., a considerable proportion, perhaps the bulk of the plant residues decomposed, is changed into humus. It appears that the fibrous constituent, lignin, plays an important part, and that humus consists largely of altered lignin combined with protein material, possibly of microbial origin. It will be seen that in wet soils the tendency will be for the residues of vegetation, to accumulate as humus. In extreme cases, this accumulation may proceed to the extent of peat formation. In certain types of peat, the material consists entirely of decomposed and decomposing plant residues, all connexion with the mineral subsoil being lost.

(2) *Acid humification.* In the second type of humification to be considered, the dominant factor is acidity or low base-status. The residues of vegetation growing in soils that are very poor in lime give rise to a peaty humus layer, even although aeration may be good. Heath peat, formed under *Erica* (heather), *Calluna* (ling) or *Vaccinium* (bilberry) vegetation, and coniferous forest peat are examples of the type of material formed where acid humification is dominant.

There are probably other types of humification. The dark-coloured humus of the "black earths" of Russia and the "prairie

soils" of North America does not appear to be satisfactorily explained by anaerobic humification, whilst acidity is excluded by their naturally high base-status. The soils of the humid tropics present a different problem. Here the humus is apparently much less dark in colour, so that one can easily under-estimate the amount of organic matter present.

The amount of organic matter in a soil, then, depends on (1) the rate at which organic matter is added to the soil either in the form of plant residues or as organic manures, and (2) the relative intensity of oxidative decomposition and humification. We shall, therefore, expect to find low organic matter where plant growth is scanty, as in deserts and in sand dunes, or where oxidative decomposition is favoured by warmth and aeration, as in culturable soils of the tropics. On the other hand, bad aeration due to water-logging, or acidity may encourage the conserving process of humification, and under such conditions organic matter as humus tends to accumulate.

The decomposition of the original organic tissue of the soil and of the concurrent microbial tissue is nothing more than a process of enzymic digestion. It is just as truly a digestion as though the plant materials entered the stomach of a domestic animal. The products of these enzymic activities, although numerous and tremendously varied, may be listed for convenience under three heads :

- (1) Energy appropriated by the micro-organisms or liberated as heat.
- (2) Simple end-products.
- (3) Humus.

(1) **The Energy of the Soil Organic Matter and its Transfer.**

The micro-organisms of the soil as they grow and multiply must not only have substance for their tissue synthesis but energy as well. Both of these are obtained in very large degree, but not entirely however, from the soil organic matter. All sorts of compounds are utilized as energy sources, some freely, others slowly and indifferently.

As might be expected, organic matter contains considerable potential energy, a large proportion of which is readily transformable to other latent forms or is liberated as heat. Plant tissue such as that entering the soil has a heat value of 4 to 5 kilo-calories to the gram of air-dry substance. The application of 10 tons of farm-manure, for example, containing 5,000 pounds of dry matter, would mean an addition of 9,000,000 to 11,000,000 kilo-calories of latent energy. A soil containing 4 per cent. of organic matter possesses about 80,000

pounds of dry organic substance to the acre-furrow-slice (2,000,000 pounds). This amount of organic residue carries from 150,000,000 to 180,000,000 calories of potential energy, equivalent in heat value to 20 or 25 tons of anthracite coal.

Of this large amount of relatively accessible energy carried by the soil, only a part is used by soil organisms, the remainder being left in the residues and dissipated as heat. This heat loss of energy is the final stage and represents a large and continual removal from the soil. The evolution of carbon dioxide is not only a rough measure of this but also an indication of the rate of the disappearance of the organic matter.

Energy is released from the soil organic matter for microbial use or as heat in a number of ways, of which oxidation and hydrolysis are the more common. This release and transfer of energy depend on a number of factors, especially the type of synthesis in progress and the compounds involved. The assimilation of amino-acids by organisms, for example, does not require much energy of exchange since these nitrogen compounds become a part of the protoplasm with only little modification. Nitrates, on the other hand, require a great energy expenditure because of the involved synthesis necessary. Energy transfer is thus extremely complex and exceedingly variable.

Certain estimates made at the Rothamsted Experiment Station, on two plots of the Broadbalk field are rather suggestive. It was calculated that 1,000,000 kilo-calories an acre were lost annually from the untreated soil while 15,000,000 kilo-calories were dissipated from the soil receiving liberal supplies of farm-manure. The magnitude of this loss is obvious. Assuming, as already suggested, that the average soil contains 150,000,000 kilo-calories of total organic energy to the acre and that the annual dissipation is 10,000,000, one-fifteenth must be the yearly loss, a surprisingly rapid turnover of the organic matter, such figures, estimates though they are, emphasize the amount of food necessary for the support of the soil organisms and the difficulty that is usually encountered in maintaining a suitable amount of organic matter in arable soils.

This turnover represents biochemical activity and, while it is very costly and results in an exorbitant loss of organic matter, it is an absolute necessity. Otherwise the soil would not function adequately either as a foot-hold or as a source of nutrients for higher plants.

(2) **Simple Products of Organic Matter Decomposition.** As

the enzymic changes of the soil organic matter proceed and humus is gradually built up, simple products begin to manifest themselves. Some of these, especially carbon dioxide which is given off in large volume, appear immediately, while others, such as nitrate nitrogen, accumulate only after the peak of the vigorous decomposition is over and the general purpose decay organisms have diminished in numbers. Since these simple end-products are readily lost, they sink to a minimum unless fresh material is added at frequent intervals.

The simple products that result from soil biochemical processes, may be listed according to the principal elements involved :

Carbon .....  $\text{CO}_2$ ,  $\text{CO}_3^{--}$ ,  $\text{HCO}_3^-$ ,  $\text{CH}_4$ , elemental carbon.

Nitrogen.....  $\text{NH}_4^+$ ,  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ , elemental nitrogen.

Sulphur .....  $\text{H}_2\text{S}$ ,  $\text{SO}_3^{--}$ ,  $\text{SO}_4^{--}$ ,  $\text{CS}_2$ .

Miscellaneous ...  $\text{O}_2$ ,  $\text{H}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{K}^+$ ,  $\text{Mg}^{++}$ ,  $\text{Ca}^{++}$ ,  $\text{PO}_4^{---}$ ,  $\text{H}^+$ ,  $\text{OH}^-$ , etc.

the various simple end products will be fully discussed later under separate headings.

(3) **Accumulation of Humus in the Soil.** Soil humus is not a stable material. As the organic matter decomposes, new humus is continually being formed, and part of the old is being completely mineralized. The equilibrium between the two processes determines the amount of humus present in a soil at a given time.

During the development of a young and immature soil the amount of new humus annually added is greater than the amount undergoing mineralization, and a gradual accumulation occurs. As the soil develops and approaches maturity, the absolute amounts of humus undergoing mineralization gradually increase until they equal the amounts of newly formed humus. From that time on, the two processes—formation and mineralization—proceed at an equal rate, and the soil may be said to have reached a state of maturity or one of equilibrium with its natural environment. The average content of humus in the mature soil remains relatively constant as long as no change in natural conditions occur, any change in the natural conditions that upsets the equilibrium will be followed by a corresponding change in the humus content of the soil.

#### BIOCHEMICAL REACTIONS AFFECTING SOIL NITROGEN.

Nitrogen is absolutely essential to the maintenance of soil fertility. This element is so necessary to the growth and repro-

duction of both plants and animals that all life would cease to exist without it.

The amounts of nitrogen found in soils vary enormously. Soils rich in organic matter contain up to 1 per cent. or more; and at the other extreme, infertile sands may contain less than 0.05 per cent. Normal figures for average and moderate fertile loams are from 0.10 per cent. to 0.30 per cent. The total amount present, however, is no guide to the amount available for the plant; the facility with which the nitrogen in its various compounds can be converted into nitrate, or some other easily assimilated combination, is the chief factor which determines the usefulness of the nitrogen.

In plant residues the ratio of nitrogen to carbon varies from about 1 : 40 to 1 : 25 (the narrower ratio is generally found in legumes). In soil organic matter (humus) the ratio of nitrogen to carbon is usually about 1 : 10, although variations between one soil and another are a little greater than were once thought.

Much of the nitrogen added to the soil undergoes many transformations before it is removed. Crop residues, green-manures, farm-manure, and other organic carriers undergo complex changes as soon as they are incorporated with soil. Proteins are converted into various decomposition products and finally their nitrogen appears in the nitrate form.

**The Natural Sources of Soil Nitrogen.** At the outset we may enquire as to the source of soil nitrogen. To say that it originates from the nitrogenous constituents of plants that have grown on the soil is only to shift the enquiry a stage further back. Plants obtain their nitrogen from the soil in the form of nitrates or ammonium salts, but we have still to account for the presence of these "available" compounds of nitrogen.

A certain amount of ammoniacal and nitrate nitrogen is contributed by rainfall. This is about 4 lbs. of nitrogen per acre per annum under temperate conditions; a small amount, but possibly of significance considered over long periods. In the tropics, where thunder-storms lead to the formation of larger amounts of nitrogen oxides in the air, the annual contribution of ammoniacal and nitrate (principally nitrate) nitrogen in rainfall may amount to as much as 50 lbs. per acre, which is an appreciable accession to the annual nitrogen requirements of crops or natural vegetation.

Whilst, even under temperate conditions, the cumulative effect of ammoniacal and nitrate nitrogen in rainfall on the nitrogen

reserves of the soil cannot be ignored, it is probable that the fixation of nitrogen by bacteria is of greater importance. The fixation of nitrogen by bacteria associated with leguminous plants is a familiar story, but fixation by free-living nitrogen fixing bacteria is probably of equal importance, and we must also take into account possible fixation of nitrogen by certain algae. Little is known of the way in which bacteria synthesize organic compounds from the chemically inert nitrogen of the atmosphere. Of the importance of this fixation there is no doubt. Not only does the great family of leguminous plants obtain its nitrogen by this means, but the nitrogenous compounds built up by the free-living nitrogen-fixing bacteria readily undergo decomposition into the simpler forms of nitrogen requisite for the growth of non-leguminous plants.

**Availability of Soil Nitrogen and the Nitrogen Cycle.** It is a remarkable fact that although an acre of soil may contain several thousand pounds of nitrogen in organic combination, a dressing of nitrate of soda or sulphate of ammonia, giving 15 or 20 lbs. of nitrogen, often produces an appreciable increase in the crop yield. It is obvious that by far the greater proportion of the soil nitrogen is not immediately available for the use of plants. Since plants require their nitrogen in the form of nitrates of ammonium salts, the processes whereby complex organic nitrogenous compounds are broken down are of great importance for plant nutrition. This breakdown, of which the final stages are:—ammonium salts-nitrites-nitrates, is the work of a variety of fungi and bacteria, although the last two stages are the work of specific bacterial species.

Except in acid soils, the change from ammonium salts to nitrates via nitrites is more rapid than the production of ammonium salts. Therefore, ammoniacal nitrogen only occurs in traces, except in acid soils. In the same way the change nitrites→nitrates is more rapid than the change ammonium salts→nitrites. Hence the proportion of nitrites is vanishingly small. Viewed as a whole, nitrification, the production of nitrates is favoured by moisture, aeration and warmth. It is inhibited by low temperature, drought, lack of aeration, and excessive acidity.

It remains to be noticed that fresh organic matter undergoes ammonification in the soil far more readily than humified organic matter, which is relatively resistant to biological attack by fungi and bacteria. It does not follow, however, that the addition of fresh organic matter to the soil always results in an immediate increase

in the amount of ammoniacal or nitrate nitrogen. When organic matter that is poor in nitrogen undergoes bacterial decomposition, the organisms concerned themselves require available nitrogen, and there may thus be a decreased supply for the use of crops, with consequent depression of plant growth. On the other hand, highly nitrogenous materials, such as dried blood or fish meal, are rapidly broken down, and soon provide available nitrogen for plant growth.

When large amounts of nitrogen are present in the soil, together with fresh organic matter, under intermittent anaerobic conditions, losses of nitrate may occur through denitrification, whereby free nitrogen is liberated. Such losses are unlikely to occur under ordinary conditions. Losses of nitrates also occur in drainage.

This interlocking succession of reactions, reversible, infinitely recurrent, and largely biochemical constitutes what is known as the nitrogen cycle, it is diagrammatically represented in (Fig. 7).

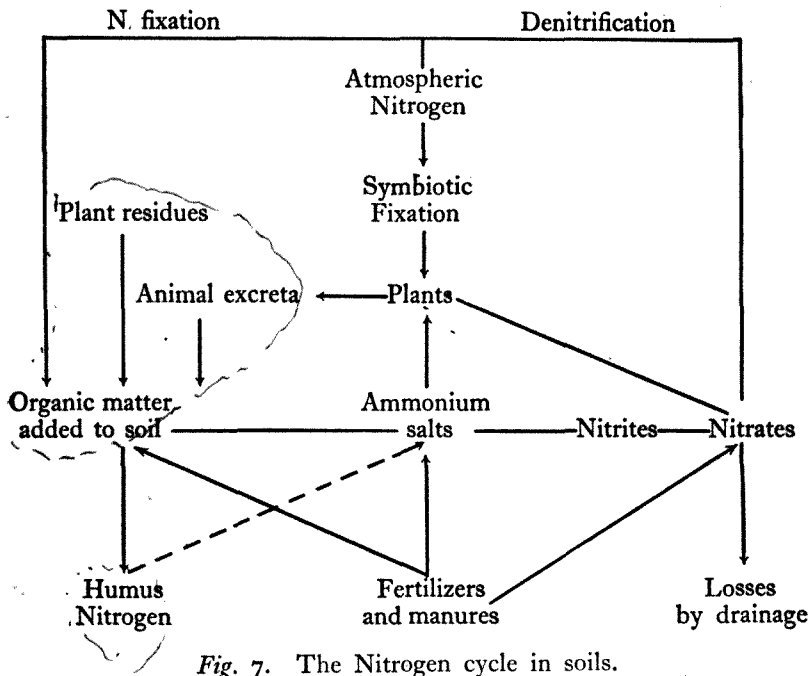
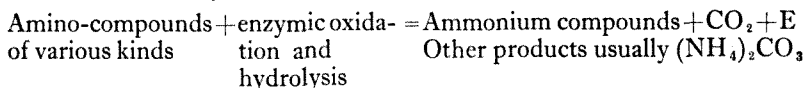


Fig. 7. The Nitrogen cycle in soils.

Now the major biochemical processes affecting the soil nitrogen will be discussed in more detail.

**Ammonification.** The transformation of the amino-compounds to the ammonium form by organisms that are able to acquire energy by the change, is called ammonification from the chemical nature of the end-product.

The same general-purpose organisms that facilitate decay are able to bring about ammonification. In so doing they not only tap ready sources of energy but no doubt also appropriate some of the nitrogen made mobile by their efforts. The enzymic process, as shown below, may be either oxidation or hydrolysis.



In the acquisition of energy by ammonification, the micro-organisms evolve great amounts of carbon dioxide and leave behind a number of by-products other than the ammonium compounds. Of the latter, ammonium carbonate is most prominent, as is to be expected when the abundance and activity of carbon dioxide is considered.

While ammonification seems to proceed to the best advantage in well-drained aerated soils with plenty of active basic material present, it will take place to some extent under almost any condition, due to the great number of different organisms capable of accomplishing the change. It may be noted here that a high pH seems to favour the intake of  $\text{NH}_4$  ions by plants, possibly because under such conditions the absorbing surfaces of the rootlets carry a negative charge. Also at a high pH there is more chance of the acidity, developed by the acid radical accompanying the  $\text{NH}_4$  ions, being neutralized.

**Photo-ammonification.** In recent years Dhar, and his co-workers, have brought forward evidence to show that nitrification and ammonification in soils are not entirely due to the action of bacteria but can also be brought about at the surface of suitable catalysts under the influence of light. Carbett has confirmed the results of these investigators. Zobell has also shown that nitrification in sea-water cannot be due to bacterial action. By taking some solutions of ammonium salts and exposing them to sunlight with sea water and magnesium carbonate he found that oxidation of ammonia to nitrate occurs. Fraps and Sterges have, however, expressed some doubt regarding the validity of the photo-chemical view. Fazal-Uddin observed that sodium nitrite is oxidised to

nitrate in the presence of zinc oxide and sunlight. Dhar and co-workers also noticed oxidation of nitrite in dilute solution when exposed to sunlight in the presence of zinc or ferric oxide. Gopala Rao and Murty have investigated the photo-decomposition of nitrate to nitrite : they have found that this occurs as a reversible reaction in sunlight transmitted by glass in the presence of ferric oxide or sterilized red soil. Moreover, they have made a very interesting observation that during the photo-dissociation of nitrate, any ammonium salt present will undergo simultaneous oxidation to nitrite.

It thus appears that many reactions hitherto ascribed to bacteria in the soil can also be brought about by sunlight with soil as a photocatalyst. The results obtained by Rao and Narayana on the photo-ammonification of amino-acids in sunlight in the presence of humic acid are tabulated below.

TABLE 5

Amino acid	Amount of ammoniacal nitrogen formed in mg. per litre	
	60 hours	120 hours
Alanine ... ..	32.42	64.21
Aspartic acid ... ..	21.23	42.34
Glutamic acid ... ..	21.26	42.42

It is thus evident that humic acid can function as a catalyst in the photo-chemical decomposition of amino-acids in sunlight.

The humic acid employed was extracted from black garden soil with 5 per cent. sodium hydroxide solution and precipitated from the latter by the addition of warm 1 : 1 hydrochloric acid. 250 c.c. of M/20 solution of the appropriate amino-acid was shaken up with 0.25 gm. of humic acid and exposed to sunlight in a pyrex glass flask under strictly aseptic conditions. The amount of ammonia formed was estimated by the Folin aeration method from time to time.

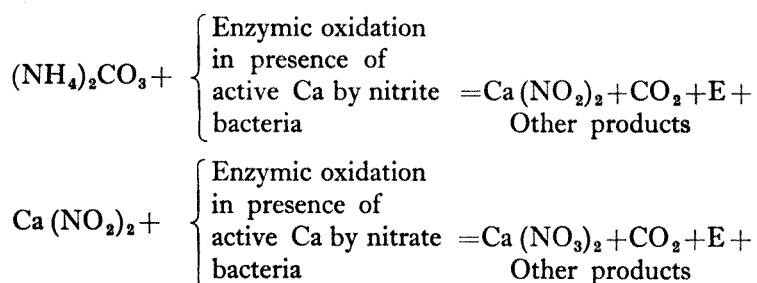
**Nitrification.** The ammonia formed by the action of soil bacteria, or added in manures, is changed to carbonate, which is then rapidly converted into nitrite, and this into nitrate, these changes proceed so rapidly that only traces of ammonia or nitrite are ever found in normal arable soils. As noted earlier the production of

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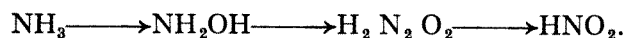
nitrites is slower than that of nitrate, while the formation of ammonia is slower still and sets a limit to the speed at which the process can take place. Thus the speed at which nitrates are formed in soil does not measure the rate of nitrification as is some times assumed, but the rate of ammonia production.

The first stage, the production of nitrite, can be brought about by a number of organisms, though only a few can do it to any important extent. N. R. Dhar, G. G. Rao, and others in India, de'Rossi in Italy and A. S. Corbet in England, support the view that it can also be effected by a purely chemical process under the influence of sunlight or ultra-violet light, but their critics object that the nitrite test is so sensitive and the possibilities of contamination so numerous, that rigid proof of chemical oxidation is exceedingly difficult to obtain.

Nitrification is a process of enzymic oxidation. The ammonium compound most readily influenced by the special-purpose bacteria involved is ammonium carbonate, possibly because this is the most common ammoniacal salt found in neutral or alkaline soils and the organisms have become adjusted to its oxidation. As shown below, the first step is the production of a salt of nitrous acid by one group of bacteria, followed immediately by its oxidation to the nitrate form. A second and distinct group of bacteria accomplish this transfer. Some of the carbon dioxide formed is freely evolved as the conversion progresses. The presence of active calcium, or some other cation seems to be necessary for satisfactory nitrification.



Mumford has shown that hydroxylamine and hyponitrous acid are intermediate between ammonium nitrogen and the nitrite.



Collectively the nitrifying organisms are called nitro-bacteria.

*Nitrosomonas* and *Nitrosococcus* are concerned in the conversion of ammonia into nitrites. The organisms having to do with the oxidation of nitrites to nitrates are generally designated as *Nitrobacter*. In practice these two groups of bacteria are usually spoken of as nitrite and nitrate organisms.

Since the conditions favouring the nitrite and nitrate bacteria are practically the same, the second transformation follows so closely on the first as practically to preclude any accumulation of the nitrite. This is fortunate, as this salt in any concentration is toxic to higher plants. As a consequence, nitrification is generally discussed as though the transformation was only one step and depended on one group of organisms. It is also probable that the photochemical oxidation may take place in tropical soils.

**Nitrate Content of Soils.** The amount of nitrate is commonly recorded as parts of nitrogen per million parts of soil ; it can be expressed as parts of nitrate of soda by multiplying by 6.06 or it can be converted into lb. per acre in the top 9 in. by multiplying by  $2\frac{1}{2}$  ; the results are not quite accurate but suffice for purposes of comparison.

The amounts of nitrate commonly found in arable soils at Rothamsted and Woburn in England are given in Table 6.

TABLE 6

*Amounts of Nitrate Found in Arable Soils at Rothamsted and Woburn*

Soil	Expressed as nitrogen			Expressed as nitrate of soda
	Parts per million		Lb. per acre	
	0-9 in.	9-18 in.	0-18 in.	Lb. per acre, 0-18 in.
Sand ... ..	5	4	25	150
Loam ... ..	10	8	46	276
Clay ... ..	10	6	38	228

In humid climates nitrates do not accumulate to any great extent in the soil, and it is very unusual to find more than 24 parts per million or 120 lb. per acre (expressed as nitrogen) in the top 18 in. It sometimes happens in dry regions that higher amounts are present, but it is usually supposed that they got there by evaporation of water which had soaked from a wide area over a particular spot.

Under humid climatic conditions the nitrates have no oppor-

tunity of persisting long but are either washed out by rain or taken up by plants. Once the stock is reduced a further quantity begins to be formed, and so far no limit has been reached to the amount of nitrate a soil can be made to yield. One of the Rothamsted plots which has been cropped with wheat every year since 1943 and has had no manure since 1839 still goes on yielding nitrate, and Table 8 shows the amounts of nitrate nitrogen contained in its various sections in November, 1935.

TABLE 7  
*Nitrate Nitrogen in Soils taken in November, 1935, from the Unmanured Plot Broadbalk*

Soil	Nitrogen, lb. per acre			Equivalent to pure nitrate of soda, lb. per acre		
	Section I	Section II	Section III	Section I	Section II	Section III
Depth, 0-18 in.	30	23	35	180	138	210
„ 0-27 in.	42	33	53	252	198	318

Section III had been fallowed during the summer : the others had been cropped.

Another piece of land is kept bare of all vegetation and is undermined in such a way that the whole of the drainage water can be collected for analysis. Ever since 1870 when the experiment began the land had yielded a large supply of nitrate, the amount being equivalent to 300 lb. of nitrate of soda per acre every year for the first 29 or 30 years, and to some 170 lb. in more recent years.

#### SOME CONDITIONS AFFECTING NITRIFICATION

Soil conditions that influence the rate and the amount of nitrification deserve practical consideration. The factors that merit special attention are :

- (1) Aeration
- (2) Temperature
- (3) Moisture
- (4) Active lime
- (5) Fertilizer salts.

(1) **Aeration.** Since nitrification is a process of oxidation, any procedure that increases the aeration of the soil should, up to a certain point, encourage it. Ploughing and especially cultivation,

therefore, are recognized means of promoting nitrification. Torinsson found in some recent experiments, that, under bare fallow nitrification was promoted by dry conditions and that application of organic matter locked up nitrate which was later released. Lime and phosphate stimulated nitrification, but the nitrate content was usually highest in the surface layer, except in late autumn. He found also that winter losses of nitrogen under fallow, were much lower than was expected, and that frost has a conservative effect on nitrate, not only preventing leaching, but also accumulating nitrate from the subsoil in the surface. He has shown also that under Swedish conditions the nitrate content of the soil is high in early spring, and a top-dressing of N is then wasteful and produces an excess of vegetative growth, but top-dressing at the end of May is recommended.

(2) **Temperature.** The temperature most favourable to the process of nitrification is from 80° to 90° F. At a temperature of 130° F. nitrification practically ceases. At freezing or below, nitrification will not take place but at about 40° F. it begins and slowly increases in intensity until the optimum temperature is reached. The lateness with which nitrification attains its full vigour in the spring is well known and nitrate of soda is sometimes used to offset it.

(3) **Moisture.** The rate with which nitrification proceeds in a soil is governed to a marked extent by the water content, the process being retarded by both very low and very high moisture conditions. Greaves and Carter found that a moisture content of about 55 per cent. of the water-holding capacity was especially favourable for nitrification.

(4) **Active lime.** It is a very common observation that lime stimulates nitrification in soils, even in those that may already contain a fair amount of active calcium. Apparently the process of oxidation requires active bases. While potassium, magnesium, and ammonium ions will allow the action to proceed, calcium gives the best results. Nitrification seems to function most vigorously when the end-product is calcium nitrate. This accounts for the feeble nitrification in acid soils and the seeming sensitivity of the organisms to a low pH. As a matter of fact, however, acidity within reasonable limits seems to have little influence on nitrification when adequate calcium is present.

In a study of six Arizona desert soils it was found that ammonia

was not completely oxidized to nitrate until the pH had been reduced to about 7.7. Nitrite may accumulate in appreciable amount, especially in very alkaline soils, but vanishes when nitrates begin to form. The process of nitrification in alkaline desert soils necessitates a decrease in pH before either nitrite or nitrate is formed; this phenomenon is held to be consistent with the hypothetical hydroxylamine-hyponitrous acid mechanism.

(5) **Fertilizer salts.** Small amounts of many kinds of salts, even those of manganese, stimulate nitrification. Sodium nitrate, unless applied in excessive amounts, promotes the nitrification of dried blood and cottonseed meal. Phosphorus is especially effective with all types of soil organisms and so intensely is it utilized that competition with higher plants results. The same is no doubt true in respect to potash salts.

#### THE FIXATION OF ATMOSPHERIC NITROGEN.

(1) **Non-Symbiotic Fixation or Azofication.** Soils may acquire a part of their nitrogen independently of higher plants, fertilizers, and rainfall. There exist in soils certain organisms which are able to use for their growth the elemental nitrogen of the soil air. The nitrogen is incorporated in the bodies of the organisms and is left in the form of proteins and related compounds. The process is called azofication because of the *Azotobacter* group of bacteria to which is ascribed a major part of the fixation. Since these organisms use the soil organic matter as a source of energy and are not directly associated with higher plants, as are the legume bacteria, the transformation is often spoken of as non-symbiotic or free fixation.

Although a great many different bacteria, and perhaps fungi also, are able to acquire small amounts of atmospheric nitrogen non-symbiotically, the greater part of free fixation in the soil is brought about by two groups of heterotrophic organisms. One of these is the aerobic *Azotobacter* of which there are several different species. The other is an anaerobic, or perhaps a facultative, bacterium called *Clostridium pastorianum*. Because of the highly colloidal nature of most soils and the great concentration of carbon dioxide at the interfaces in all soils, even when in the best of tilth anaerobic conditions may occur locally even in aerated soils. Consequently these two groups of bacteria work side by side in the synthesis of nitrogen compounds from atmospheric nitrogen.

(2) **Symbiotic fixation.** Equally or possibly more important is another large group of organisms that fix nitrogen. These are the symbiotic organisms, namely, *B. radicola*, that function in close association with the legumes and other nitrogen-gathering plants. These bacteria live in symbiosis with their hosts and have the ability to bring atmospheric nitrogen into organic combinations. The nitrogen thus fixed from the air is available for the nutrition of the host plant, from which in turn the bacteria draw their non-nitrogenous pabulum. They are aerobic organisms and appear to exist in forms associated with particular species of leguminous plants.

The amount of nitrogen added to the soil by legumes depends on the kind of legume, the condition of the stand, and the stage of growth at which the legume is turned under. No general estimate can be given. Some data are available and may be cited as illustrations of possibilities, though they are probably rarely applicable to specific conditions.

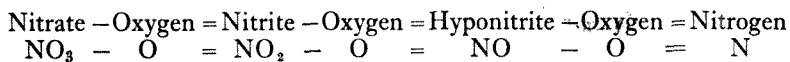
The amount of nitrogen in a legume when turned under represents the nitrogen it has taken from both the soil and the air, but the amount taken from the air is all that is really added to the soil. The relative amounts derived from each of these sources are difficult to determine, and it can only be stated that as a broad average about two-thirds of the nitrogen in a legume is believed to have been taken from the air and one-third from the soil.

For details concerning the fixation of nitrogen by legumes the reader should refer to books on soil microbiology.

## DENITRIFICATION

Though much of the work of soil organisms is beneficial to the higher plants, some organisms under favourable conditions may undo the beneficial work of other organisms. Attention is called to these harmful activities because of their bearing on certain phases of the management of the soil. Water may stand in low places for some time after heavy rains. In order to obtain oxygen under these conditions, anaerobic organisms use the energy of organic matter in order to obtain oxygen from such compounds as nitrates, sulphates, and ferric oxides. If oxygen is split off from nitrate,  $\text{NO}_3$ , it is reduced to nitrite,  $\text{NO}_2$ , which green plants cannot use, the process being called "nitrate reduction." Nitrite may in turn be reduced and the nitrogen liberated and returned to

the air as elemental gaseous nitrogen. The liberation of nitrogen in this manner is known as "denitrification." This change is thought to happen in three steps as follows :—



Similarly, sulphates and other oxygen-bearing compounds may be reduced with temporary detrimental effects. Fortunately, the practical remedy for these harmful conditions is drainage, tillage, and aeration, in short, the restoration of conditions favourable for the beneficial organisms.

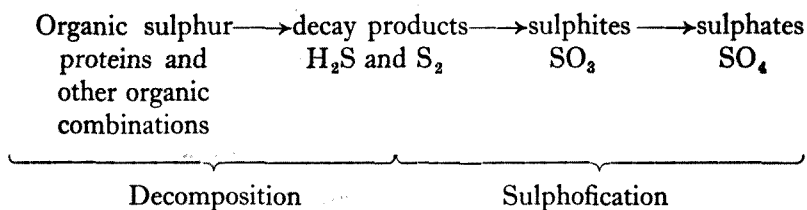
**Carbon.** Most of the energy acquired by the fauna and flora of the soil comes from the oxidation of carbon and, as a result, its oxide is evolved continuously and in large amounts.

This is the main source of this gas, although small amounts are excreted by plant roots and are brought down in rainwater. The carbon dioxide of the soil, evolved both in summer and winter, escapes in a large degree to the atmosphere, where it may be used by plants.

A lesser amount, and this is just as important a feature as the atmospheric loss, reacts in the soil, producing carbonic acid, and the carbonates and bicarbonates of calcium, potassium, magnesium, and other elements. These salts are readily soluble and may be lost in drainage or be used by higher plants. Thus not only are Ca, Mg, and K ions presented to the absorbing surfaces of micro-organisms and higher plants but  $\text{CO}_3^{--}$  and  $\text{HCO}_3^-$  ions as well. Small amounts of carbon may therefore enter plants in this way. Most of the carbon, however, is acquired by photosynthesis.

Besides carbon dioxide, carbonates, and bicarbonates, the simplification of organic matter results in other carbon products. Under certain conditions methane ( $\text{CH}_4$ ) and carbon bisulfide ( $\text{CS}_2$ ) may be produced in small amounts. But of all the simple products, carbon dioxide is by far the most important.

**Sulphur.** As in the case of the nitrogen, the sulphur transformations are largely biochemical. They go on readily in most soils and while probably subject to marked retardation at times, adverse influences are apparently not as serious, practically, as in the case of nitrogen. The transformations may be indicated in a general way as follows :—



Certain bacteria in the soil have the ability to oxidize organic sulphur compounds, sulphides, and free sulphur to sulphuric acid or sulphates. These are aerobic bacteria whose activity appears to be favoured by the presence of calcium carbonate. Sulphofication, is, like nitrification, a process of oxidation. Broadly speaking, it may be said that the same conditions which favour nitrification also favour the production of sulphate.

Sulphuric acid from the biological oxidation of organic sulphur compounds may contribute appreciably to the acidity of peat soils. P. Kottgen found that from 7.7 to 53 per cent. of the total acidity of forest peat soils was due to sulphuric acid. High base-status favours sulphofication and may thus accelerate lowering of the pH. Dressings of sulphur are sometimes applied to the soil to increase acidity.

#### OTHER BIOCHEMICAL REACTIONS IN SOIL

**Boron.** It is assumed that the underlying cause of the rapid response of limed soils to boron is to be found in the relation of boron to the biological processes of the soil. Abaturova and Naftel suggested that the great stimulation of bacterial activity accompanying the liming of acid soils might reach a point where the boron would be biologically absorbed by the increased population of micro-organisms, with the result that the higher plants could no longer obtain sufficient boron for growth. This theory is somewhat strengthened by the fact that lime-induced boron deficiency is most noticeable during the early stages of plant development, and is generally temporary, that is, with a decline in the micro-organic population boron is released for the higher plants. Further evidence in favour of the biological-fixation theory has been obtained with sterile soil cultures in which symptoms of over-liming did not occur in excessively limed soils. Water-soluble boron, however, was increased about eight times in the sterilized as compared with that in unsterilized soil. It is not possible, however, to know

whether the increase was due to decomposition of inorganic materials or organic matter, and perhaps both chemical and biological fixation occurred.

**Manganese.** Gerretsen believes certain bacteria in the soil play an important role in converting soluble manganese compounds into insoluble oxides. The precipitation of insoluble manganic oxides in the soil by micro-organisms occurs, between pH limits 6.5-7.8 coinciding, it is stated, with the limits within which the plant disease, grey-speck, is most frequent in the field. The ammonia contents of manganese-deficient plants were sometimes from two to three times that of normal plants. These ammoniacal products of decomposition, produced by bacteria in the roots of plants poor in manganese and transported by the sap stream to the leaves, appear to be responsible for the typical leaf spots of grey-speck. The resistance of the root system to invading micro-organisms depends largely on the manganese content of the plant, which determines whether certain bacteria act as saprophytes or as parasites. The lowered resistance to root-invading micro-organisms is attributed to a reduction in carbon dioxide assimilation in manganese-deficient leaves.

**Phosphorus.** It has been shown that the fixation of glycerophosphate and inorganic phosphate by soil varied markedly according to soil type and soil colloid content. With heat-sterilized soil evidence was obtained that fixation of organic phosphate by lime is due mainly to the action of micro-organisms on organic phosphate with the liberation and subsequent fixation of the inorganic phosphate. It is ascertained, however, that the soil microbes release 2-3 mg. soluble  $P_2O_5$  per 100 g. of soil per annum, which is 2-3 times as much as crops require.

*Ionic Exchange in Soils*

IONIC exchange is a property of soils that has very important practical applications. When a simple salt, such as the ordinary fertilizer constituent muriate of potash (potassium chloride), is added to a soil, it does much more than simply increase the concentration of potash in the soil solution. Instead, some potassium changes places in the colloidal particle with calcium, sodium, and other mineral base elements, and these in turn enter into the soil solution. The result is that only a part of the potassium which was added in solution remains water-soluble. The increased concentrations of other constituents set free may enrich the soil solution in other ways, and make it better balanced for plant growth. This process, by which one base goes from solution into insoluble form and another comes out into the solution to take its place, is known as base exchange. It is a great soil-conserving factor, since it retards the excessive leaching out of such valuable constituents as potash and ammonia.

Unlike the sand, the clay is chemically active : it reacts with salts as if it were itself a salt. Indeed it may be regarded as a kind of very complex salt, the acid part being a complex alumino-silicic acid, while the basic part includes aluminium, calcium, magnesium, potassium, sodium, and hydrogen. Just as there are different salts of the same general type, so there are different clays.

Water softening is a good example of base exchange. The calcium bicarbonate present in many spring and well waters interacts with soap (a sodium or potassium salt of a complex fatty acid) to form a calcium soap which is a hard curd and useless for washing purposes. So the water is called "Hard." The process of water softening consists in replacing the calcium by sodium. The water is allowed to pass through a layer of granules of an insoluble sodium aluminium silicate ; this reacts with the calcium bicarbonate in the

water to form insoluble calcium aluminium silicate and sodium carbonate which goes into solution. The water has not lost its saline matter but has replaced calcium by sodium (which neither wastes soap nor scales boilers). Periodically the calcium aluminium silicate needs "regeneration," i.e. reversion to the original sodium compound : this is done by allowing a strong solution of sodium chloride to pass through the cylinder and the water that passes out is run to waste. The changes that take place are :—

(1) During water softening :

sodium aluminium silicate + calcium bicarbonate (in hard water)

= calcium aluminium silicate + sodium bicarbonate (in soft water)

(2) During regeneration :

calcium aluminium silicate + sodium chloride

= sodium aluminium silicate + calcium chloride.

When calcium chloride ceases to appear the regeneration is complete.

Likewise, it is possible by base exchange to improve soils in which physical conditions have become bad from excess of sodium. Hydrogen or calcium may be substituted for a part of the sodium. Sometimes exchange is accomplished by the addition of sulphuric acid in small-scale operations, or sometimes by the addition of calcium salts, such as calcium chloride, in irrigation districts. Base exchange takes place rapidly by the action of water on soil colloids under natural conditions. The traces of carbonic acid in the water replace lime and other constituents to form a colloid of increasing hydrogen content ; that is, to form a more acid soil. Thus, when soil leaching has been excessive over long periods, soil acidity becomes an agricultural problem, both from the standpoint of intensity of the acidity and also from that of the depletion of various soil bases taking place through the base-exchange process.

An interesting instance of base exchange phenomena is found in the land reclamation work which has been going on for many centuries on the North Coast of Holland. The silt deposited by the sea is allowed to accumulate until there is a sufficient area of it to justify the building of a dyke to prevent further incursions of the sea. The silt which is deposited, having been in contact with sea water, is essentially a sodium complex, but in addition, there is a large amount of calcium carbonate particles. Within a year or so of the dyking-in the surplus sea salt is almost entirely removed in the

drainage water, and the calcium carbonate proceeds to react with the sodium clay, gradually bringing about the formation of calcium clay.

The development of colloidal chemistry during the latter half of the last century proved an important aid to the study of absorption reactions, and suggested the explanation that these phenomena, though chemical, are distinguished from ordinary chemical reactions by the fact that they are localized at surfaces. Absorption is, however, incomplete ; for, even with the most dilute solutions, a certain proportion of the absorbable ion remains in solution. G. Wiegner, from a review of available data, showed that the relationship between the concentration of an ion in the solid phase—the soil—and the concentration in the equilibrium solution could be expressed by the so-called Freundlich equation :  $y = KC^1/p$ , where  $y$  is the amount of the ion present in unit weight of soil,  $C$  the concentration of the ion in the solution, and  $K$  and  $p$  are constants.

**Ionic Exchange Materials in Soils.** Until about ten years ago practically all soil workers had believed for more than three-quarters of a century that the important property of soils known as “base exchange” is a function of amorphous substances. The idea was firmly established that the exchangeable ions are either held by some vaguely defined force called “absorption” or else are chemically combined as compounds of unknown identity. However, the discovery that the different clay minerals possess base-exchange properties in varying degrees, has led, of course, to a new approach to the subject of base exchange.

For a number of years certain soil workers held that, apart from humus material, base exchange in soils is due to a single substance which was designated the “base exchange substance.” It is now definitely established, however, that there is no one single base-exchange substance in soils ; rather, there are several such substances. These are found mainly in the so-called “clay fraction” of the soil, and among them the clay minerals play a large part. Montmorillonitic clays stand at the head of the list. This type of clay comes nearest to being the ideal base-exchange substance of soils, but other clay minerals have the property of base exchange to some extent ; the mica-like clays have rather marked base-exchange power.

Jacob A. Hofmann and others claim that clay minerals are the only kind of inorganic substances of soils having any important base-exchange significance. The clay minerals also have a limited amount of anion-exchange power. P. R. Stout has recently shown

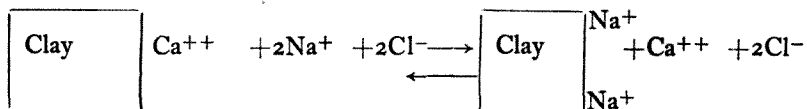
that the exposed OH-ions of kaolinite and halloysite may be exchanged for  $\text{PO}_4$ -ions, thus accounting for the marked phosphate-absorbing power of these clays. The importance of this discovery lies in the fact that certain soils known to contain kaolinitic clay have extraordinary phosphate fixing power. These newly established facts led the present author to choose "Ionic Exchange" as the title of this chapter instead of the old popular title "Base-Exchange."

It should be also noted that the ions of the soil are not absorbed in a proportionate manner, but rather disproportionately. K- and  $\text{NH}_4$ -ions are for the most part bound to the mica, Ca-ions to the humus and Mg-ions to the montmorillonite. Since the Ca-ions are generally in excess, both the montmorillonite and the mica hold a variable amount of Ca-ions by selective sorption. This disproportionate distribution also holds for H-ions and for Fe- and Al-ions.

**Nature of Ionic Exchange.** We have already mentioned the varying capacities of different clay minerals for undergoing the base exchange reaction, and we must now consider this reaction in detail as it is, next to photosynthesis, the most important chemical reaction in the whole domain of agriculture. In the reaction between soils and electrolytes, the outstanding experimental facts are :—

The nature of the reaction which we term base exchange is already familiar as a general property of the outer, mobile ions attached to negatively charged colloidal particles.

(1) The reaction is so quick as to appear instantaneous. This fact is very significant to the chemist. It means that the reaction occurs between charged ions, not between electrically neutral molecules. It is correct therefore to represent such reactions by the following equation :—



This shows clearly that the reaction is between the cations only.

(2) The reaction is always reversible. In the example just given, no sooner have the sodium ions attached themselves to the clay and the calcium ions replaced them in the outer solution than these also begin to react with one another giving clay saturated with calcium ions and sodium ions in solution. The speeds of the forward and the reverse reactions are generally different so that the mixed system

which results seldom contains equal proportions of adsorbed bases. If, however, we wish the reaction to proceed to a finish in any particular case we can always force it by removing the soluble product as quickly as possible and treating the clay or soil with more of the original solution. In this way we continually reduce the concentration of the original ion and hence the effectiveness of the reverse reaction, until finally the latter ceases. Starting, for instance, with a clay associated with only calcium ions, we could prepare the corresponding clay associated only with sodium ions by washing continuously with fresh sodium chloride solution. It is this kind of continuous washing or leaching which is so important in soil formation processes, as we shall see later.

(3) We must now consider the effectiveness of the various cations as displacing agents in base exchange reactions. It is interesting to note that the divalent cations are more effective as displacing agents in base exchange reactions than the monovalent ones, and for ions of the same valency the effectiveness increases as the hydration of the cations entering decreases. Thus we see that potassium enters by exchange more readily than sodium, calcium more readily than potassium and so on. There is one exception to the rule that monovalent ions are less effective than divalent ones. The hydrogen ion far transcends other monovalent ions and is comparable with calcium and barium in its power of replacement. We may ascribe all this peculiarity to its minute size and simple structure.

The relative energy with which bases enter the absorbing complex is shown by some results obtained by A. F. Joseph and H. B. Oakley who allowed equimolecular solutions of calcium, potassium, and sodium chlorides, of strength 0.5 normal with respect to chloride to percolate through a soil. With calcium and potassium chlorides, the ratio Ca/K attained in the soil was 0.9; with calcium and sodium chlorides the Ca/Na ratio was 6; and with potassium and sodium chlorides the K/Na ratio was 6. It appears, therefore, that the energy of replacement of calcium is slightly greater than that of potassium and that both greatly exceed sodium in this respect.

We see, therefore, that in base exchange any cation may be taken up by a soil and that, once held, it may subsequently be displaced by any other cation. The persistence or retention of a cation depends both on the extent to which it is taken up and on the likelihood of its displacement later. These conclusions are of

importance in two respects. They enable us to give a logical explanation of many processes of soil formation and to predict the consequences arising from the application of fertilizers.

**Amount of Exchangeable Bases in Soils.** Exchangeable bases are generally expressed as milligram-equivalents of base per 100 gm. of dry soil. To avoid repetition of this awkward phrase, E. M. Crowther has proposed that the unit be called a "Way." The numbers of these units range from 5 or less in poor sandy soils to 15 in moderately poor heavy soils, about 40 in more fertile heavy soils and 50 or more in prairie soils or chernozems. In neutral or nearly neutral conditions in temperate climates calcium commonly forms about 80 per cent. or more of these bases, magnesium about 10 to 15 per cent. the rest being chiefly sodium and potassium (see Table 8).

TABLE 8

*Percentage Composition of Exchangeable Bases from Various Acid or Neutral Soils*

Soil	100 Parts of Exchangeable Base contain								
	Chernozem, U.S.S.R., Gedroiz	Podsol, U.S.S.R., Gedroiz	Clay, Holland, Hissink	Sandy humus, Holland, Hissink	Various, Scotland, Smith	Various, U.S.A., Calif., & Brown Kelly & Brown	Rothamsted, England, Page & Williams	Woburn, England, Crowther & Basu	
Ca ... ..	82.1	80.5	79	96	88	63	92	79	
Mg ... ..	15.1	13.4	13	13	7	25	5	13	
K ... ..	2.7	6.1	2	3	2	4	3	3	
Na ... ..	Nil	Nil	6	8	3	8	—	5	
Total in mg. equiv. per 100 grms. soil ...	54.8	6.2	38.3	19.8	11.2	30.3	14.7	5.2	

In the statement of results of exchangeable base determination it is convenient to use milligram equivalents rather than the actual percentages of exchangeable bases. A milligram equivalent is the equivalent weight in milligrams, so that 1 mg. equivalent of CaO = 0.028 g. A percentage of CaO is thus converted to mg. equivalents by dividing by 0.028. The mg. equivalent content of the other bases is computed in the same way.

The exchange cations are irregularly distributed with regard to soil type. In black soils they are mainly Ca and Mg; in podzol soils 80-96 per cent. of the exchange cations is H. In solonetz soils Na is 50-70 per cent. of the exchangeable bases.

It has been shown recently that apart from Ca, Mg, K and Na, other cations are absorbed by the soil. E. Endredy using a photometric method sensitive to 0.04 mg. of manganese, found that the usual variation of the exchangeable manganese in the soil is 0.0-0.2 milli-equivalents of Mn for 100 gms. of soil. Larger amounts were found only in acid soils containing significant amounts of organic matter. He also showed that cultivation diminishes the amount of exchangeable manganese. Exchangeable iron is also reported in some acid soils. It was about 0.0001 per cent. of the exchangeable manganese. V. C. Jamison has confirmed the absorption of copper from copper salts by several sandy soils and found that it was a function of copper concentration.

**Mechanism of Ionic Exchange.** Liebig held that the absorption of ammonia and other bases by the soil was a physical process. This was long considered to be incompatible with Way's chemical hypothesis, but, the two views are reconciled in the modern conception of salts as electrically charged atoms or atom-groups held together primarily by the physical force of electrostatic attraction. The electric components of a simple salt, the ions, dissociate from one another on dissolving in water and migrate when an electric current is passed through the solution. The positive ions move with the current (i.e. downstream) and so are called cations, while the negative ions, the anions, move against it. The soil complex, however, differs from a simple salt in that only the positively charged components are ions in the strict sense of the word: the negative charges are situated on particles so large, that under ordinary soil conditions they cannot dissolve but remain entangled with the rest of the solid matter. When soil is stirred up with water the complex does not dissolve but the cations dissociate, and under the influence of an electric current migrate and can be separated from the anions by means of a cell just as in ordinary electrolysis, leaving an acid residue in the anode chamber. This process, under the name of electrodialysis is used as an alternative method for the separation of exchangeable bases. It has also been used to render soils and their constituents completely "unsaturated," i.e., free from exchangeable base, though the product is liable to contamination by decomposition products.

During the passage of an electric current through wet soil water is carried forward with the cations: this process is called electrical endosmosis. A number of practical applications of this property

have been made ; e.g., if a ploughshare in passing through the soil is maintained at a negative potential a film of water is deposited on it and acts as a lubricant, thereby reducing the draught of the plough.

If a calcium clay is subjected to electro dialysis in a suitable cell, calcium hydroxide can be collected in the neighbourhood of the cathode, and the hydrogen clay complex, that is the acid, in the neighbourhood of the anode. The truly acid nature of the hydrogen complex is shown by the electrometric determination of the hydrogen ion concentration of suspensions. If a hydrogen clay is suspended in water there is a definite and measurable hydrogen ion concentration which decreases as the suspended particles fall. This phenomena which has been investigated by Wiegner seems clearly to show that there are actual hydrogen ions associated with the clay particles and which do affect an electrode in the same way as the hydrogen ions of a soluble acid.

There is a connection between the replacing power of a cation and the properties of the soil containing that cation. Cations which have the lowest replacing power tend to produce in soils a stickiness and a high degree of dispersion, whereas cations which have the greatest replacing power tend to produce opposite properties. A sodium soil, for example, tends to be very sticky, to have its particles more highly dispersed, and to remain for a long time suspended in water. A calcium soil, on the other hand, has these sticky properties reduced to a minimum, the particles are well aggregated together, and settle out from aqueous suspensions relatively quickly.

It has been pointed out by Wiegner that when all other circumstances are the same those cations which have the greatest replacing power are least hydrated, i.e., have a relatively small number of water molecules combined with them, whereas those cations which have the least replacing power and produce the more sticky complexes, are those which are most heavily hydrated. The heavily hydrated cations presumably become less intimately associated with the soil colloids than do those which are less encumbered by attached water molecules. Differences in the degree of ionization of the compounds concerned, however, sometimes allow of a more highly hydrated ion having a greater replacing power than a less hydrated ion. For example, calcium has a greater replacing power than barium although it is more highly hydrated.

**Base Saturation and Unsaturation.** The exchangeable cations held by natural soils are mainly confined to calcium,

magnesium, sodium and potassium, and in most approximately neutral soils the calcium comprises about 80 per cent. of these. In "alkali" soils sodium is usually present in greatest amount and is accompanied by potassium and sometimes magnesium and calcium. When the whole of the absorptive power of the soil is satisfied with metallic cations the soil is said to be saturated. When hydrogen ions are among the cations the soil is unsaturated.

In some of the older literature the word "unsaturated" is applied to acid soils, but that is not usual now. It is important to understand the difference between an unsaturated soil and an acid soil. A fully saturated soil along with water is an alkaline system quite comparable to the salt of a strong base and a weak acid, e.g., sodium phosphate. The system will only be neutral when a definite amount of the cations are replaced by hydrogen ion, just as phosphoric acid will be exactly neutralized, by much less than its chemical equivalent of sodium hydroxide.

When salts react with unsaturated soils hydrogen ions naturally participate in the exchange phenomena. They will not, however, exceed the hydroxyl ions in solution and incur acidity unless either the soil or the salt is itself acid. When neutral salt solutions are applied to the acid soils the solutions become acid to a much greater extent than when pure water is applied, because of the ionic exchange whereby H ions come into solution.

Generally aluminium ions also appear in solution when neutral salt solutions are applied to acid soils. There is considerable difference of opinion as to whether the aluminium goes into solution by a straightforward process of base exchange, or whether hydrogen ions go thus into solution and the acid so formed decomposes a part of the soil complex and so brings the aluminium into solution.

One may visualise four different conditions of the soil crumb, so far as their reactive cations are concerned :—

1. A soil may be saturated with calcium, etc., and have in addition a reserve of calcium bicarbonate. Such a soil is alkaline.
2. A soil may be saturated and have no reserve of calcium bicarbonate. Such a soil is alkaline.
3. A soil may be unsaturated. Such a soil may be alkaline, neutral, or acid according to the ratio of hydrogen ions to other cations.
4. A soil may be unsaturated and yet have a reserve of calcium carbonate.

## DEGREE OF UNSATURATION AND EXCHANGE CAPACITY

The content of exchangeable bases at saturation, expressed in milligram-equivalents, is termed the exchange capacity. Much ingenuity has been shown in devising methods for determining the extent of unsaturation of acid soils, i.e., the amount of base required to produce saturation. The difficulty consists in arriving at a satisfactory definition of saturation. For, even when a soil contains such a proportion of exchangeable bases that its reaction is neutral (pH 7.0), it can still combine with more bases. The case is parallel, as mentioned above with that of a weak acid such as acetic acid. If a strong alkali such as soda be added to a given amount of acetic acid in dilute solution, the quantity of soda added when the neutral point is reached is less than the equivalent of acetic acid present. When the soda is exactly equivalent to the acetic acid the reaction of the solution is markedly alkaline owing to hydrolytic dissociation.

**Change in the Exchange Capacity of various Soil types in relation to Soil Reaction.** F. R. Yatsevich found that the exchange capacity within the pH interval 4.5-8 was, as a first approximation, a linear function of the pH. At high pH values a deviation from the linear relation in the direction of an increase in the exchange capacity was found. This deviation was more marked the higher the content in organic substances and sesquioxides. On the basis of the linear relation between the exchange capacity and the pH value it is possible to calculate how the exchange capacity of a soil will be changed by certain procedures used in cultivation, e.g., liming. On altering pH of a chernozem soil from 2 to 13 V. I. Daramonova found that exchange capacity increased approximately tenfold, the relationship being almost linear.

**Buffering Capacity of Soils.** If varying amounts of acid or alkali are added to a given suspension of soil in water and the pH is determined after equilibrium has been attained it is possible to obtain so-called buffering curves. This may be exemplified by some data obtained by W. Brenner. Ten-gram portions of soil were shaken in flasks, each containing 30 c.c. of water, to which varying amounts of 0.1 N-hydrochloric acid and 0.1 N-calcium hydroxide, respectively, had been added. After allowing to stand for 24 hours with frequent shaking, the pH was determined electrometrically. Results for typical soils are shown in Fig. 8. The curve NN represents a blank experiment without soil. The divergence of an

individual buffering curve from this curve gives a measure of the amount of interaction between the soil and the acid or alkali. It will be seen that for the blank, indicating only slight interaction, the curves for clay and raw humus show considerable divergence from this. In the curve of sand, it will be seen that, whilst 2 c.c. of acid

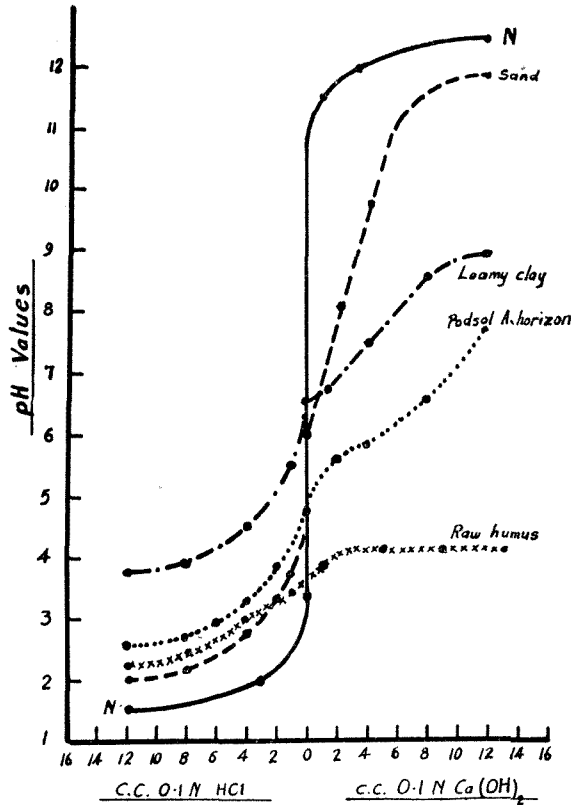


Fig. 8. Buffering curves of soils.

cause a change of about 2.75 in pH, 2 c.c. of alkali cause a change of about 2.0 in pH. The sand is said to be more strongly buffered on the alkaline than on the acid side. Comparing the change in pH produced by the addition of 5 c.c. of alkali, we have for the sand 4.5, for the loamy clay, 1.3, for the podsol (A) horizon 1.0 and for raw humus 0.2.

If we measure the buffering capacity by the amount of alkali

required to produce a given change in pH, the order given by the curves would be raw humus, podsol A-horizon, loamy clay, and sand. In general we may say that the buffering capacity of soils depends on their content of reactive colloidal material. It is to be noticed that soils show buffering both on the acid and alkaline side. They are said to be amphoteric, i.e., exhibiting both basic and acidic properties. This is to be expected since the colloidal complex contains both acidoid and basoid components.

**Factors Affecting the Exchange Capacity.** It has been already stated that the property of base exchange in soils resides in the colloidal complex, which is composed of clay and humus. The exchange capacity will therefore depend on the proportions of each of these constituents present in the soil and also on their individual exchange capacities.

Varying figures are obtained for the exchange capacities of clay and humus according to the nature and origin of the materials, and the methods employed for determining exchange capacity. For colloidal clay, the figures obtained by S. Mattson, using the method of leaching to equilibrium with neutral calcium chloride solution, range from 0.164 to 1.102 mg. equivalents per gram, the lowest figure being given by lateritic clay and the highest by bentonite. Estimates for the exchange capacity of humus vary from about 2.5 mg. equivalents per gram.

Considering saturation to be represented by the base-status of soils which have long been in equilibrium with excess of calcium carbonate, R. Williams has sought to determine the relative base-binding capacity of clay and organic matter. The data are shown in Table 9.

Organic carbon has been used as a measure of the humus and two figures have been obtained in each case, namely, total carbon, and organic carbon removable by prolonged boiling with 4 per cent. hydrogen peroxide. The latter determination was made in order to avoid the error in total carbon introduced, in some cases, by the presence of the fragments of coal and cinder which are so frequent in cultivated soils.

By the use of a graphical method, equations were obtained for the relationship between total bases (T), clay (K), total carbon ( $C_t$ ), and oxidizable carbon ( $C_o$ ). The relationships thus found are :

$$\begin{array}{l} T = 0.57 K + 4.55 C_t \quad \dots \quad \dots \quad (1) \\ \text{and} \quad T = 0.57 K + 6.33 C_o \quad \dots \quad \dots \quad (2) \end{array}$$

TABLE 9

*Relation between Total Exchangeable Bases, Clay Content, and Organic Carbon Content for Carbonate Soils*

Soil	Clay %	SiO <sub>2</sub>		Organic carbon		CaCO <sub>3</sub> %	Total bases in mg. equivalents calculated by		Total bases in mg. Equivalents %
		R <sub>2</sub> O <sub>3</sub> of Clay	Total	Oxidisable	Formula 1		Formula 2		
Vaynol Clay ... ..	63.5	2.33	0.64	0.14	13.6	39.1	37.1	36.8	
B 1459 ... ..	45.0	3.24	1.54	0.96	8.3	37.8	36.8	36.7	
G 109 ... ..	41.7	2.73	4.45	2.43	7.0	44.0	39.1	40.0	
Harpden ... ..	24.7	2.01	1.06	0.59	4.1	18.8	17.8	18.6	
G 26A ... ..	39.3	4.78	2.54	2.06	3.6	34.1	35.4	34.4	
G 115A ... ..	27.5	2.56	1.94	1.45	3.3	24.5	24.8	25.9	
G 130A ... ..	34.3	2.84	3.14	2.22	3.1	33.85	33.5	33.0	
Llysfasi ... ..	27.0	3.79	2.29	1.83	3.1	25.8	26.9	23.6	
Rendzina ... ..	59.6	3.13	1.63	1.30	2.7	41.4	42.2	46.4	
Groes Ffordd ... ..	—	2.01	1.89	1.58	2.6	13.9	15.3	16.1	
F 85 ... ..	24.8	2.61	2.09	1.36	2.4	23.65	22.7	22.5	
G 157 ... ..	21.2	1.79	2.39	1.91	2.2	23.0	24.2	23.2	
D 129 ... ..	33.6	1.69	3.34	2.62	1.7	34.3	35.65	32.0	
G 206 ... ..	23.6	1.99	7.21	3.07	8.0	46.25	32.8	35.7	
G 178 A ... ..	47.1	n.d.	3.62	2.95	3.3	43.3	45.4	58.7	
G 57 ... ..	22.9	n.d.	2.98	1.84	0.8	26.6	24.6	13.6	
F 111 ... ..	19.0	n.d.	3.28	2.20	0.5	25.8	24.7	19.3	
Ab. 3-5 ... ..	22.4	n.d.	3.17	2.36	0.2	27.2	27.6	14.5	

The calculated values are shown in columns 6 and 7 respectively.

The exchange capacity indicated for clay, namely, 0.57 mg. equivalents per gram falls within the limits found by S. Mattson and is in good agreement with a figure obtained by E. M. Crowther and H. K. Basu for Woburn soils.

In general, 0.5-1.0 m.e., per gram has been accepted as the range to be expected for the base exchange capacity of mineral soil colloids. It is to be noted, however, that these values are dependent on particle size. Even if  $2\mu$  can be accepted as the upper limit of size for active clays, the exchange capacity must depend on the relative particle distribution. Mattson has shown also the importance of chemical composition, in particular the  $\text{SiO}_2 : \text{R}_2\text{O}_3$  ratio, in determining exchange capacity.

This ratio is calculated as follows :—

$$\frac{\% \text{ SiO}_2}{\text{Molecular wt. of SiO}_2 (60.1)} = A$$

$$\frac{\% \text{ Al}_2\text{O}_3}{\text{Molecular wt. of Al}_2\text{O}_3 (101.9)} = B$$

$$\frac{\% \text{ Fe}_2\text{O}_3}{\text{Molecular wt. of Fe}_2\text{O}_3 (159.7)} = C$$

$$\frac{A}{B+C} = \text{Silica : sesquioxide ratio.}$$

The investigation of the base status of some Scottish profiles on basic igneous parent materials by Mitchell and Muir, has disclosed that some lower horizons, free from organic matter, have a base exchange capacity of up to 9 m.e. per gram of ( $2\mu$ ) clay. Table 10 shows some of the results obtained :—

TABLE 10

Soil	$\text{SiO}_2/\text{Al}_2\text{O}_3$	Clay content	Exchange capacity	m.e. per gm. Clay
479V	1.55	16.0	35.2(32.9)	2.2
5048	3.83	11.6	42.5(43.0)	3.7
5044	4.05	10.7	41.8(39.0)	3.9
4784	5.95	9.8	42.1(38.9)	4.3
5001A	8.40	15.7	88.0(98.6)	5.6
5002	2.16	3.8	34.8(29.6)	9.1

The exchange capacity figures used were obtained by the Parker method. Those in brackets are the sums of the individual exchangeable cations. The agreement between the two sets of figures demonstrates the truly exchangeable nature of the cations.

**Effect of Temperature upon the Exchangeable Bases of Soils.** J. S. Andrews found that after the clay fraction of a soil was heated to from 25° to 100°C. for from 5 to 46 days, replaceable K, Ca and acid H decreased, whereas replaceable Na and Mg increased with prolonged treatment.

**Composition of the Exchangeable Cations.** I. N. Antipov found that after deep ploughing and mixing the lower (illuvial) horizons of solonetz and forest-steppe soils with the upper layers, a uniform composition of the exchangeable bases is attained at the end of two months. Other experiments have confirmed Antipov's belief that mixing the horizons decreases the degree of alkalinity in alkaline soils and of unsaturation in podzol soils.

**The Mode of Combination of Cations with Soil Colloids.** The mode of combination of cations with soil colloids has been much investigated. A distinction is commonly made between exchangeable and non-exchangeable cations, the former being those which go into the aqueous phase when a soil is treated with a neutral solution. There is, however, no sharp distinction between exchangeable and non-exchangeable cations; when soil is repeatedly treated with a neutral salt solution ionic exchange proceeds at first readily, but with increasing difficulty as the remaining ions become decreasingly "exchangeable." The cations appear to be bound either on or within the crystal lattice of the mineral soil colloids, and their exchangeability is a function of their orientation with respect to the anionic part of the soil complex and seems to vary with the nature of the sorbed cations. The word *sorb* is now preferred to adsorb or absorb as being more general and implying nothing about the hypothetical physical nature of the sorption process.

It was formerly assumed that the sorbed cations were more or less evenly distributed over the surface of the humic colloids and clay minerals. On this assumption it was possible to arrange the cations in a series of increasing "energy of adsorption" which increased both with the valency and with the atomic weight of the cations. Recently published work by P. Schachtschabel, however, who leached soils with solutions of mixed salts, has shown that the relative proportions of the different cations entering into the exchange

reaction when equilibrium is established vary widely according to the nature of the sorbing complex, i.e., according to whether it belongs to the kaolin, montmorillonite or mica group (see chapter 16). Thus, with a mixed calcium-ammonium solution the sorbed cations on a humus colloid in equilibrium with the extracting solution consisted of 30 per cent. Ca and 10 per cent.  $\text{NH}_4$ . These proportions were reversed with mica, while kaolin and montmorillonite sorbed both ions about equally strongly.

On the basis of this selective sorption of ions by different soil colloids a method has been worked out for estimating the relative share of the separate colloids in the total sorption capacity of a soil. The sorption characteristics of samples of the pure clay minerals were first studied, and the results were used to interpret data similarly obtained by leaching soils with a mixed solution of barium and magnesium chlorides. The share of the organic colloids was estimated by determining the sorption capacity before and after treatment with hydrogen peroxide.

Schachtschabel points out that these sorption studies do not give an actually quantitative picture of the composition of the sorption complex. This can be obtained by X-ray analysis. Sorption analysis defines the surface characteristics of the complex in terms of the constituent minerals. From the practical point of view X-ray analysis provides information on the nutrient reserves and total productive capacity, while sorption analysis provides information on the physico-chemical activity, of the soil. In this connection Schachtschabel refers to the particular significance of mica to soil fertility. In buffer capacity mica greatly exceeds montmorillonite, kaolin and humus. It is the principal carrier of potash which it sorbs strongly. According to the rule that the exchangeability of an ion is greater the higher the degree of saturation, mica gives potash up more readily to plants than would be the case if the potash were evenly distributed among all the soil colloids. The same is apparently true of  $\text{NH}_4$ , whereas Ca and Mg are loosely sorbed by mica, and highly micaceous soils are often very susceptible to excess or deficiency of lime. For this reason the presence of certain amounts of montmorillonite and humus, which strongly sorb divalent cations, is indispensable to fertility. Much further work, however, is required to define the role of each colloid type or group in the phenomena of ionic exchange, but if this can be achieved the practical control of soil productivity will have been brought nearer.

**Anionic Exchange.** The sorption of anions by soil colloids has long been established. This sorption is readily demonstrable in the case of certain anions such as  $\text{PO}_4^{--}$ , but the work of S. Mattson has shown that even anions such as chloride which are not sorbed by ordinary soils may be sorbed by certain colloids. This behaviour is illustrated by a series of experiments in which equal weights of soil colloids desaturated by electro dialysis were treated with solutions of ammonium chloride, ammonium sulphate, and ammonium phosphate respectively, the proportion of cation to anion being varied by adding different amounts of ammonia and the respective acid. Similar results were obtained for the sorption of  $\text{SO}_4^{--}$  and  $\text{PO}_4^{--}$  ions, the energy of sorption being in the order,  $\text{Cl}^- > \text{SO}_4^{--} > \text{PO}_4^{--}$ . In general, colloids having low silica-sesquioxide ratios (i.e., acidoid-basoid ratios) more readily sorb anions and pass over to the electro-positive state than do colloids having high silica-sesquioxide ratios.

The displacement of anions from the absorbing complex has been less studied than that of cations, but recent investigations have demonstrated its occurrence. A. Demolon and E. Bastisse have shown that certain anions, for example, citrate, silicate, and oxalate ions, can produce exchange alkalinity, due to displacement of hydroxyl-ions. They also demonstrated the liberation of phosphate ions and suggested that silicate ions may play a part in the mobilization of phosphate in the soil solution. S. Ravikovitch, in studies of the sorption and liberation of phosphate ions by soils, found that phosphate can be liberated by addition of calcium hydroxide or sodium hydroxide to soils. The liberation of phosphate ions takes place after cationic exchange has proceeded to completion and an excess of hydroxyl-ions is sorbed by the complex.

W. Laatsch showed that the removal of  $\text{PO}_4^{--}$  on shaking phosphate solutions with Ca-permutite and with Ca- and  $\text{NH}_4$ -montmorillonite takes place by sorption on the surface of the mineral and not by precipitation of insoluble phosphates. He also found that the sorption capacity of the clay-humus complex is less than that of pure clay. This is of practical importance, as the phosphates are thus rendered more available to vegetation.

J. B. Kelly and A. R. Midgely found that hydroxyl ions, of which ferric oxide is a good source, strongly fix phosphate ions, and that kaolin fixes phosphate only when it is so finely ground as to expose active OH-ions. Ferric hydroxide and a podsol B horizon brought large amounts of phosphate into an unavailable form. When a

suspension of these materials was mixed with soluble phosphate of similar pH, the pH of the mixture rose. This is taken to indicate that phosphate replaced the hydroxyl ions. Silicate and fluoride ions are similarly supposed capable of replacing OH-ions; the beneficial effect of silica on plant growth may be due to its ability to remove fixed phosphate or to replace the OH-ions and thus decrease phosphate fixation.

H. F. Murphy treated samples of kaolinite and montmorillonite with  $\text{KH}_2\text{PO}_4$  solution and subsequently leached them with distilled water. The kaolinite leachate contained practically no phosphate indicating a high degree of fixation, whereas a positive test for phosphate was obtained from montmorillonite leachates even after leaching with 3 litres of water. In pot tests the availability to plants of the kaolinite phosphate was lower than that of the montmorillonite phosphate. It was concluded that the phosphate sorbed by montmorillonite is mainly occluded, whilst that fixed by kaolinite is chemically bound. C. A. Black has adduced evidence that phosphate ions replace hydroxyl ions on the lattice layers inside the kaolinite crystal as well as those exposed on the outside. J. G. Baldwin and J. S. Hosking, working with a strongly fixing kaolinitic clay loam showed that the phosphate-fixing power was much reduced by liming, and attributed the effect to a lowering of the anionic exchange capacity with rise of pH and consequent release of sorbed phosphate.

**The Ultimate pH of the Soil.** The ultimate pH of the soil, i.e., the pH after all diffusible anions and cations have been removed, as in electro dialysis, depends on the relative dissociation of the acidoid and basoid components. The principal acidoid components of the soil are silicic acid and humic acids, and the principal basoid components are alumina and ferric oxide. Where  $K_{\text{acidoid}} > K_{\text{basoid}}$ , the reaction is on the acid side of neutrality. This is the case even with the most markedly basic soil colloids such as that of the Nipe clay. Mattson obtained the following pH values for suspensions of four typical colloids after electro dialysis.

Nipe	Cecil	Sassafras	Sharkey	Humus
6.65	4.75	4.63	3.73	3.72

The corresponding  $\text{SiO}_2/\text{R}_2\text{O}_3$  ratios for the four mineral colloids were 0.31, 1.34, 1.89, and 3.18, respectively.

Mattson considers the soil colloids to be analogous to isoelectric precipitates. The colloidal material of the soil, according to this

hypothesis, has a complex constitution and varies in properties according to the proportion of acidoid to basoid groups. We may contrast colloids of an acidoid character having low isoelectric pH, low ultimate pH, feeble anionic sorption, and high base exchange capacity, with colloids of basoid character, having high isoelectric pH, high ultimate pH, strong anionic sorption, and low base exchange capacity. The former are represented by colloids rich in silicic acid and humus, the latter by colloids rich in sesquioxides.

J. A. Prescott has shown that there is a straight-line relationship between the pH values of electrolysed soils and the  $\text{SiO}_2/\text{R}_2\text{O}_3$  ratio of their clays. The regression equation connecting the values is

$$\text{Ultimate pH} = 5.06 - 0.488 \times \frac{\text{SiO}_2}{\text{R}_2\text{O}_3}$$

The problem of the constitution and reactions of the soil colloidal material is being actively investigated from different standpoints and a full discussion would lead into regions of physical chemistry beyond the scope of the present book.

**Base Exchange and Plant Nutrition.** Some recently published works by American authors, notably H. Jenny and R. Overstreet, have suggested that the commonly held belief that plants get all their nutrients from the soil via the soil solution requires modification. According to Jenny and Overstreet, complete dissolution of soil minerals is not an essential prerequisite for their absorption by plants. They present evidence of a process of direct or "contact" exchange between bases sorbed on colloidal clay particles and on the surfaces of roots. Barley roots immersed in, or continuously leached with, distilled water lost an insignificant quantity of potassium to the water and similar results were obtained when the roots were immersed in dilute solutions of salts and hydrochloric acid. On the other hand, immersion in suspensions of bentonite, partially or completely saturated with hydrogen and basic ions, resulted in losses up to 90 per cent. of the original potassium content of the roots. In potassium-hydrogen clay suspensions the roots increased their potassium content by 28.5 per cent. and decreased their calcium content by 22.2 per cent.; in calcium-hydrogen clay the roots took up calcium ions (6.4 per cent.) and lost potassium ions (19 per cent.). In experiments in which the roots and the clay suspensions were separated by a membrane allowing the passage of sorbed cations, but not of clay particles, no appreciable loss of potassium from the roots occurred; in the absence of

contact between the roots and clay, no ionic exchange took place through the intervening solution. It is suggested that contact exchange becomes a predominant process in root absorption when the level of exchangeable nutrients or the degree of saturation of the soil is low. H. Jenny and A. D. Ayers found that the intake of potassium by barley roots decreased with decreasing degree of saturation for potassium, and that the decrease was affected by the nature of the replacing cation.

## CHAPTER 8

### *The Colloidal Complex and its Physico-chemical Properties*

THE importance of the physico-chemical properties of soils in relation to plant growth has rarely been thoroughly appreciated. The ability of the soil to produce crops is dependent not only upon the proper supply of nutrients but also upon the physico-chemical properties of the soil. Due to the great advance which colloidal chemistry has achieved in recent years, such soil properties have been studied with some profit. In the present chapter we will deal with the most important of these properties.

The physico-chemical properties of the soil are governed mainly by :—

- (1) The constitution of the inorganic colloidal material.
- (2) The nature and content of the exchangeable bases present
- (3) The relative proportions of organic and inorganic colloidal material.

The most important physico-chemical properties are the following :—

- (1). Plasticity.
- (2). Cohesion.
- (3). Flocculation.
- (4). Swelling.
- (5). Shrinkage.
- (6). Adsorption of water molecules.
- (7). Heat of wetting.
- (8). Viscosity.
- (9). Structure.

#### (1) PLASTICITY

When a small amount of colloidal clay is dispersed in a much larger quantity of water, a condition designated by the colloidal

chemist as a sol exists. When this relationship is reversed and the relatively small quantity of water is immeshed in the interstices and crevices between and within the porous micelles, a viscous condition results. The colloidal mass is now called a gel. Field soils, because of the limited amount of water usually present are normally in the gel condition.

Most gels, especially the siliceous clays of humid regions, exhibit plasticity, that is pliability and the capacity of being moulded. This property is probably due to the plate-like nature of the clay particles and the lubricating yet binding influence of the adsorbed water. The property can be exhibited also by finely ground lamellar minerals such as mica and biotite. It is more strongly developed in soils with highly siliceous clay fractions than in soils whose clay fractions contain large proportions of sesquioxides. Table II shows the Plasticity Number of different soil types.

TABLE II  
*Plasticity Data for Some Typical Soils*  
(Atterberg)

Soils	Upper Plastic Limit % Water	Lower Plastic Limit % Water	Plasticity Number
(a) Highly Plastic Soils—			
Silurian Clay ... ..	67	40	27
Ancyus Clay ... ..	57	30	27
Glacial Clay ... ..	51	26	25
(b) Moderately Plastic Soils—			
Fresh-water Clay ... ..	52	37	15
Arable Soil ... ..	42	30	12
Glacial Clay ... ..	32	25	7
(c) Freshly Plastic Soils—			
Arable Soil ... ..	64	58	6
Arable Soil ... ..	33	28	5
Arable Soil ... ..	22	18	4

## (2) COHESION

A second characteristic closely related to plasticity is cohesion. As the water of a clay gel is reduced, shrinkage occurs and various structural forms develop depending on the nature of the soil involved. The shrinkage, which splits the soil mass into aggregates, is accompanied by a cohesion of the particles which makes the structural

developments more or less permanent. This tendency of the clay particles to stick together probably is due, at least in part, to the mutual attraction of the water molecules carried by replacable cations.

Cohesion is closely associated with plasticity, for plastic soils are cohesive and set into hard clods on drying. It is markedly affected by changes in moisture content and, in heavy and medium-textured soils, increases as the soil dries. The intractable clods formed in the drying out of heavy clay soils are familiar to cultivators. With extremely light sands, however, cohesion may pass through a maximum with decreasing water content and then decrease as complete dryness is approached. This is exemplified by the looseness of sandy soils when completely dry.

### (3) FLOCCULATION

Flocculation, a term applied to a coagulation of matter in the colloidal state, is an outstanding characteristic of most clayey soils. As already stated various positive ions are held by the colloidal nuclei in a replaceable condition. For some reason, as yet not very satisfactorily explained, calcium and hydrogen ions promote granulation by the phenomena of flocculation.

A very good example of flocculation is afforded by treating a colloidal clay suspension with a little calcium hydroxide. The tiny clay particles almost immediately coalesce into floccules, and, because of their combined weight, sink to the bottom of the containing vessel, leaving the supernatant liquid clear. The phenomenon is called flocculation because of the peculiar appearance of the aggregates. The same granulating action apparently takes place in the soil itself, but of course with less rapidity and under conditions hardly noticeable to the eye.

The coagulating capacity of the various cations is in the order,  $H > Ca > Mg > K > Na$ . This is fortunate in the humid regions as the colloidal complexes of humid region soils are usually dominated by calcium and hydrogen. Therefore such soils tend to assume a coagulated condition in the field and granulation is greatly promoted. Just why hydrogen and calcium cations are so effective in this respect is difficult to say, although it is probably related to the electrical potential of the particles, their degree of hydration, and their migration velocities. An excess of active potassium and especially sodium tends to work in the opposite direction and accounts for the dispersed

and sticky condition of certain alkali soils and for the undesirable physical effects of large applications of nitrate of soda as a fertiliser.

The flocculating power of simple salts depends on the metallic cation and on any secondary reactions that may occur between them and the clay. Chlorides present the simplest case, base exchange being the only important secondary action taking place. Among the alkali metals, lithium chloride is the weakest and caesium chloride is the strongest flocculant ; the order is



Of the alkaline-earth metals, magnesium chloride is probably the weakest though it is stronger than most of the alkali chlorides ; and barium is the strongest with calcium intermediate. Aluminium and iron chlorides are still more powerful flocculants, but important secondary actions result from the high hydrogen-ion content of their solutions. The nitrates and sulphates behave similarly to the chlorides. Soluble carbonates, such as sodium carbonate, react with the alkaline earth clays to give sodium clay and the insoluble alkaline earth carbonate before any flocculating action can take place, and complex or polyvalent anions such as silicates or phosphates are adsorbed on the clay surface and so alter its properties.

**Theory of Flocculation.** The particles of a suspension carry electrical charges, usually negative and the condition for independent behaviour is that their potential shall be above a certain critical value. When, for any reason, the potential of the particles falls below this value, the electrostatic repulsion is insufficient to prevent the association of particles into compound aggregates. The nature of the force whereby such aggregates are held together has been differently explained as cohesion, as co-ordinate valency, or as linkage through common cations.

Two stages are distinguished in coagulation. The first stage, which is reached when the potential of the suspended particles falls below the critical potential, is slow coagulation. If the potential is further lowered, coagulation becomes increasingly rapid until it reaches a maximum in instantaneous coagulation, or flocculation.

Coagulation of suspensions can be brought about in one of the following ways :

(1) By addition of electrolytes to the suspension medium. This results in a repression of the dissociation of the outer cations, whereby cations moving freely in the solution rejoin the colloidal particle, with

the consequence that a proportion of the free charges on the inner sheath anions is neutralised.

(2) By decreasing the degree of hydration of the cations, as for example, by addition of alcohol. This has the effect of decreasing the radial distance between the inner and the outer sheaths. The same effect is produced when highly hydrated cations such as lithium and sodium are replaced by less hydrated cations such as potassium, calcium or hydrogen.

(3) By increasing the dielectric constant of the medium.

The stability of suspensions in terms of their associated cations is in the order  $\text{Li} > \text{Na} > \text{K} > \text{Rb} > \text{Cs} > \text{Mg} > \text{Ca} > \text{Sr} > \text{Ba} > \text{H}$ . This is also, apart from the uncertainty in the case of hydrogen, the order of hydration of the ions.

Since the stability of suspensions depends on the charge of their particles, it follows that, so far as we are dealing with negative suspensions, the more marked the acidoid character of the colloidal particles, the greater will be the electric charge and the higher the electrokinetic potential. This is, in fact, the case: clays having a high silica-sesquioxide ratio are more stable than clays having a low silica-sesquioxide ratio. Thus, whilst it is possible to prepare stable suspensions of highly siliceous clays with hydrogen as the cation, with clays of a lateritic character, i.e., with a low silica-sesquioxide ratio, the hydrogen clays are unstable, and stability can be attained only by the introduction of a highly hydrated ion such as sodium.

#### (4) SWELLING

**Principles of swelling.** According to Katz a solid swells when it takes up a liquid without losing its apparent homogeneity as its volume is enlarged and its cohesion is diminished. This concept, attempts to distinguish sharply between capillary intake and swelling. Recently, however, greater emphasis has been placed on the forces acting in the swelling process. Although practically all substances that possess the capacity to swell also have the common property of a large existing or potential surface, the different physico-chemical characteristics of the swelling solids, as well as of the liquid, play exceedingly important parts in the process, thereby making it extremely difficult to explain swelling by any single physical or physico-chemical phenomenon.

Swelling is always accompanied by a volume contraction of the total system even though the dimensions of the solid material are

enlarged. That is, if 1 c.c. of solid is placed in 1 c.c. of water, the total volume will be less than 2 c.c. This volume contraction is primarily associated with the compressibility of the water during adsorption, probably as a result of oriented packing of the water molecules. There may be changes in the degree of association of water molecules.

It has also been shown that the swelling of colloidal clays increases with the silica-sesquioxide ratio of the colloid and varies with the nature of the adsorbed cation. The expanding-lattice types of colloids (montmorillonite) swell considerably more than the fixed-lattice types (halloysite, kaolinite). This suggests the possibility of two types of swelling, namely, intermicellar and intramicellar. Hofmann, Endell and Wilm have demonstrated through X-ray techniques that the montmorillonitic clays have an expanding lattice and exhibit intramicellar swelling on wetting. The majority of the data indicate, however, that intermicellar swelling is probably the more important.

**Concepts of swelling.** It is obvious that the swelling of soil colloids is a rather complicated physico-chemical phenomenon. Experimental results suggest certain interpretations of swelling in terms of the colloidal chemistry of the surface, that is, the effect of both the inner and outer parts of the electrical double layer in their relation to charge and hydration. It is interesting to compare these interpretations with the deductions of other investigators. Katz has studied extensively the swelling of a large number of substances of widely varying character. Care was taken that swelling was not complicated by mechanical factors such as the porosity of the systems. From his experimental results Katz has calculated, with the aid of thermodynamical reasoning, certain relationships between swelling pressure, heat of swelling, relative vapour pressure, etc. He compares the behaviour of swelling substances to that of an ideal concentrated solution, the heat of dilution of which can be entirely changed into other forms of energy. Evidently the swelling of soils and clays is more complicated ; but there is reason to believe that the orientation of molecules on the surface of clays as a result of the electrical properties of both the liquid and the surface may follow the laws developed by Katz.

The swelling of clay particles is, however, a consequence of their chemical activity, although the problem is complicated in detail and has not yet been worked out. Suppose we imagine a clay crumb to

contain water-filled fissures. The exchangeable bases are partly dissociated as positive ions, leaving the clay particle charged negatively. Both the ions and the water molecules are in continuous motion, known as thermal agitation. When the crumb is immersed in water, the ions can never stray very far from the parent crumb, for they are attracted back by the force between the positive and negative charges (unlike charges attract, like charges repel). The uncharged water molecules are, on the other hand, free to wander out into the external water and to be replaced by molecules of this latter. It is as though the crumb were surrounded by a membrane, through which water can pass out but within which the ions are retained. Now, the external water molecules approach the membrane and enter the crumb at a greater frequency than the internal water molecules approach the membrane and leave, for only a fraction of the molecules moving inside are water molecules, the remainder being the ions which are always turned back by the membrane. Hence on balance there is a passage of water into the crumb with consequent swelling. This behaviour varies both with the number and kind of ions dissociated by a given amount of clay.

China clay, for example, dissociates very few ions and swells very little. The stability of the crumbs, or resistance to complete disintegration when wetted, seems to be linked in some way to the percentage of calcium ions among the exchangeable bases, although not so definitely as was once thought.

It is very interesting to note that when the Gezira (Sudan) was first irrigated, the swelling of the clay was so great as to force the masonry of the regulators out of position, sometimes as much as 10 cm., thereby causing considerable trouble.

#### (5) SHRINKAGE

If clay or a clay soil is uniformly moistened and then allowed to dry out, it will shrink and crack. This is true of particle systems generally. It has been shown by Haines at Rothamsted that the diminution in volume as the clay dries out is exactly proportional to the amount of water which is evaporated until the amount of water remaining reaches a certain critical amount. After this the amount of shrinkage becomes much smaller in relation to the water lost. This, however, is not true of moist kaolin (which has no hydrophilic properties) the shrinkage of which continues to be proportional to the water lost so long as there is any shrinkage (*see Fig. 9*).

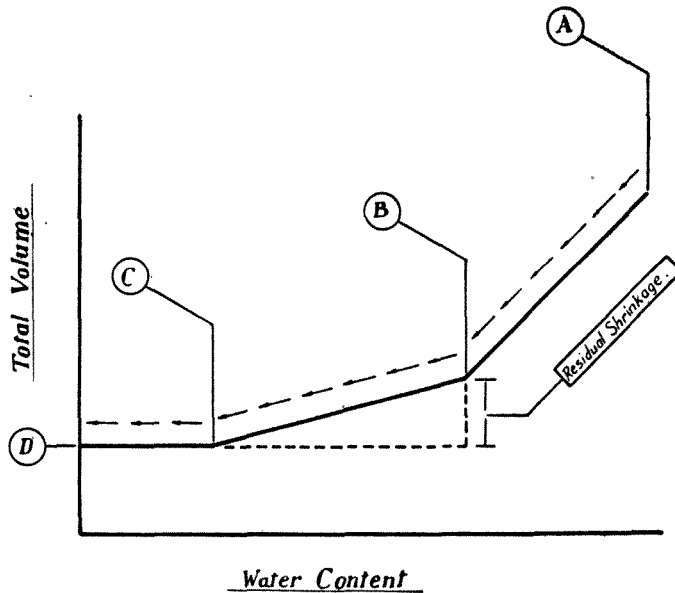


Fig. 9. The shrinkage of clay on drying.

#### (6) ADSORPTION OF WATER MOLECULES

**The Concept of Hygroscopicity.** When a sample of dry soil is placed in an atmosphere of water vapour, it will adsorb water molecules until an equilibrium is established between the soil and the atmosphere. The amount of water adsorbed increases with the clay content (specific surface), the vapour pressure of the water molecules in the atmosphere surrounding the soil and with decreasing temperature.

Rodewald developed the theory of water adsorption on the thermo-dynamic basis of the Clausius equation and showed that the water content of hygroscopic bodies is related to temperature and vapour pressure. The heat absorbed by a hygroscopic body at constant temperature was considered as equivalent to the work used to separate the water molecules from the surface and to change liquid molecules to the vapour phase. Consequently, if heat must be applied to a hygroscopic soil to loosen water molecules and to change them into water vapour, heat must be evolved during the adsorption of water molecules if a dried soil is placed in water. This evolution of heat is known as the heat of wetting. Rodewald

visualized the heat of wetting as being due to the total energy released by the adhesion of water to the surface. This value was then considered to be proportional to the force with which water molecules were attracted to the surface.

**Effect of Adsorbed Ions on Hygroscopicity.** Thomas has studied the effect of various replaceable bases on the vapour pressure curves and had found that the K-, Na- and  $\text{NH}_4$ -saturated soils absorb less water than the H- and Ca-saturated samples at low vapour pressures. At high vapour pressures the Na-saturated soils adsorb the largest amount of water. Thomas attributes the peculiar form of the curve for Na-soils to the greater dispersion and swelling at higher moisture contents plus the possibility of the existence of hydrates of the colloidal minerals present.

It appears from the numerous investigations of the adsorption of water molecules by colloidal clays that adsorption is a function of the attractive forces in the surface of the particles. These forces are associated with the chemical and mineralogical nature of the crystal lattice and the hydration of the adsorbed cations. Dehydration studies of colloidal clays have furnished some clues as to the nature of these forces.

Studies of the rate of water loss of various colloidal materials as a function of temperature have shown that water is lost at a uniformly decreasing rate up to rather high temperatures. For example, as illustrated in (Fig. 10), a permutite gradually loses water up to about  $700^\circ\text{C}$ . There is no break in the curve to suggest a difference in the form of water. Apparently, the last traces are held in the colloidal pores with great tenacity. Putnam clay loses water similarly to permutite up to about  $350^\circ\text{C}$ ., when a sharp increase in water loss occurs. This increase in water loss is explained as a shattering of the crystal lattice. Bentonite continues to lose water up to about  $550^\circ\text{C}$ . before there is a shattering of the crystal. Most of the original water in the bentonite is lost below  $150$  to  $200^\circ$ .

Undoubtedly, absorbed water is not completely expelled at  $110^\circ\text{C}$ ., which is the customary temperature for removing the so-called hygroscopic water. Water that is driven off from  $110^\circ\text{C}$ . to ignition is generally termed combined water. This is not technically correct even though the choice of  $110^\circ\text{C}$ . may be analytically convenient. In light of recent results, it seems logical to consider combined water as that water which is an integral part of the crystal-

lattice makeup. It is significant to note that the effect of the adsorbed cations on water adsorption and release is only apparent up to a temperature of about 300°C.

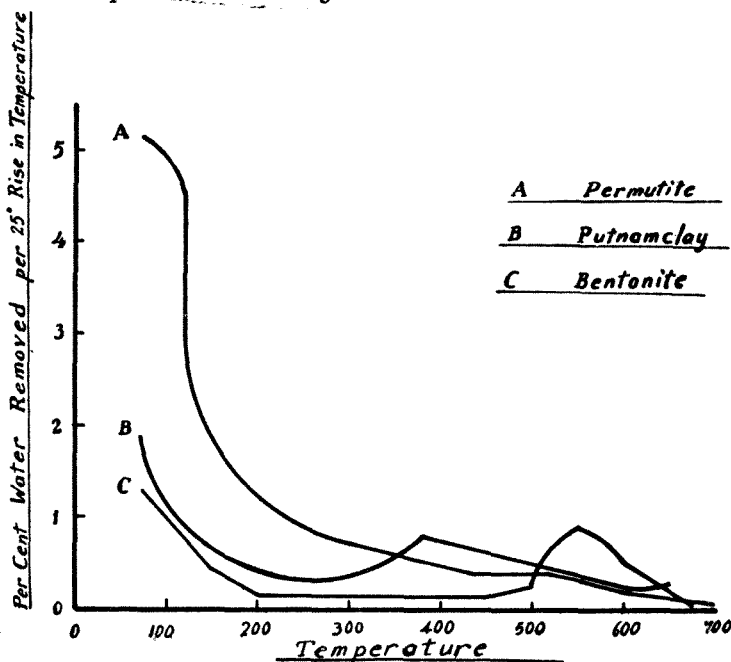


Fig. 10. Dehydration curves of permutite, clay and bentonite.

The property of adsorption of water molecules by colloids has been used as a measure of the colloidal activity of the soil. It is based on the assumption that the colloidal fraction is the only portion of the soil that absorbs water. For example, the quantity of moisture adsorbed from a saturated atmosphere over 3.3 per cent.  $H_2SO_4$ , by a given weight of colloid extracted from a soil and spread in a thin layer, is determined. A similar determination is made on a sample of the soil itself. The colloidal content is then calculated by the equation :

$$\frac{H_2O \text{ adsorbed by 1 gram of soil}}{H_2O \text{ adsorbed by 1 gram of colloid}} \times 100 = \% \text{ colloid content}$$

### (7) HEAT OF WETTING

A dry soil evolves heat when placed in contact with water. This heat of wetting is an index of the energy of adsorption of water.

Essentially, it represents the loss in kinetic energy of water molecules during adsorption.

**Factors Affecting Heat of Wetting.** Mitscherlich and his co-workers studied the relationship between moisture content and heat of wetting and observed a gradual lowering of the heat evolved as the soil contained more original moisture. That moisture content at which no heat of wetting was obtained was then characterized as the true hygroscopicity of the substance. Their investigations pointed out also the importance of specific surface on the heat of wetting inasmuch as heavier-textured soils always evolved more heat on wetting than coarser-textured ones. These effects are illustrated in Fig. 11. It is noted that the heat of wetting decreases to zero

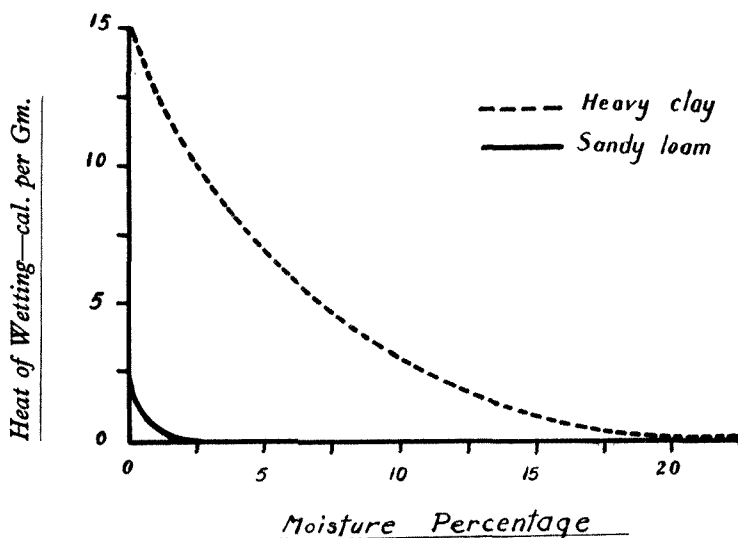


Fig. 11. The relation of the heat of wetting to moisture percentage and clay content. (Data of Mitscherlich.)

as the moisture content increases. The zero value (hygroscopicity) for the sandy loam occurs at a much lower percentage than for the clay. Moreover, the dotted line curve shows that clay has about 8 times the heat of wetting of the sandy loam curve. Kapp has shown that quartz particles larger than  $5\mu$  do not exhibit heat of wetting. Smaller fractions show heat of wetting, but not as much as clay particles of the same size. Particles larger than  $5\mu$  that have been fractionated from various soils evolve small amounts

of heat on wetting, but only about one-tenth as much as the truly colloidal fractions.

The nature of the clay mineral and the type of exchangeable cations have similar effects on the heat of wetting as on hygroscopicity. This is necessarily so because of the interrelationship of the two phenomena.

The heat of wetting has been used as a measure of the colloidal activity of the soil. The fact that the nature of the colloid as well as the amount influence the magnitude of the heat of wetting (and hygroscopicity) led Anderson and others to use the ratio method for estimating the colloid content of soils. The heat of wetting, is determined for both the soil and the extracted colloid. On the assumption that the colloid fraction contributes practically all the heat of wetting to the soil as a

whole, the ratio  $\frac{\text{Heat of wetting of soil}}{\text{heat of wetting of extracted colloid}} \times 100$  gives the approximate percentage of colloid present.

#### **The Effect of Heat on the Extractable Constituents of Soil.**

It was noted many years ago that if a soil is gently heated over a bunsen burner for a few minutes, the amounts of iron, aluminium, phosphate and other constituents which can be extracted by dilute acid, are considerably greater than the amounts extracted in the same way from the non-heated soil. No reasonable explanation of this could be put forward at the time it was observed. The increased quantities dissolved from the heated soil must be due to one of two general causes. Either iron, etc., compounds have been converted into some more soluble form, or else a greater amount of the surface of the particles containing these compounds has been exposed to the attacking acid. The first of these is a most unlikely explanation, for the effect of heat upon such compounds as are here involved is usually to depress their solubility. A greater exposure of the surface of soil particles must therefore be brought about by this gentle heating. Now if the soil crumbs, all having gelatinous coatings, are bunched together in the soil, the effect of a gentle heat will be to dehydrate and shrivel up this gelatinous material, as a result of which the particles will tend either to fall apart or in the first stages of sintering to form very porous aggregates and to admit the easy access of an acid solution subsequently applied. Particles (e.g. ferric hydroxide), which are artificially covered with particles of

gelatinous silica show this same phenomenon of giving up a greater amount of iron to an extracting acid after gentle heating.

### (8) VISCOSITY

**The Nature of Viscosity of Colloidal Suspension.** The viscosity of a liquid refers to the internal friction between the molecules of the liquid. In a colloidal solution it is assumed that the particles are hydrated and that friction arises between the water molecules of the water hull and those of the dispersion medium. Colloids are generally divided into two distinct groups, hydrophile (or lyophile) and hydrophobe (or lyophobe), with respect to their viscosity. Hydrophilic sols are characterized by a relatively high viscosity. The hydrophobic colloids do not possess a viscosity appreciably different from that of their dispersion medium. Clay soils can be considered as occupying an intermediary position, being neither truly lyophilic or lyophobic. Colloidal clays possess the properties of hydrophilic colloids because of their hydration. Sensitivity to electrolytes is a hydrophobic characteristic.

Viscosity measurements have been rather extensively used for the characterization of lyophilic colloids, even though most of the work has been more or less relative in nature. It has been fairly well established that the viscosity of colloids is a function of the volume occupied by the disperse phase. This volume should include that of the particle and any water of hydration that may be associated with it. Einstein has proposed a formula showing the relation between viscosity and the volume of the dispersed phase. His equation indicates that any increase in viscosity, in a colloidal system depends on the total volume of the particles and is independent of the degree of dispersion. This formula is,

$$\eta_s = \eta_m (1 + 2.5 \phi)$$

where  $\eta_s$  is the viscosity of the colloidal system,  $\eta_m$  the viscosity of the dispersion medium and  $\phi$  the volume of the dispersed phase per unit volume of sol.

This equation assumes that the particles are spherical and rigid. The values of  $\phi$  also includes any water of hydration associated with the particles.

Numerous investigators have observed that the addition of small amounts of electrolytes to colloidal systems produces a sharp drop

in their viscosity. Further additions either produce no change or cause an increase in viscosity, depending upon the nature of the colloid and the type of electrolyte.

Kruyt calls this change in viscosity the electroviscous effect, by which is meant that the change in relative viscosity is due to the electrical charge on the particle. As this charge increases, viscosity also becomes greater, and vice versa. Pauli, on the other hand in discussing the colloid chemistry of the proteins, attributes their physico-chemical behaviour to their degree of ionization. Hydration of protein particles increases with ionization. Since variations in viscosity are due to differences in hydration, viscosity is a function of the degree of ionization of the protein.

Weigner considers the hydration of ions as playing the important role in the viscosity of clays. Particles containing hydrated ions on their surfaces are voluminous and viscous in pure water. Those particles containing weakly hydrated ions around the primary particle have a lower viscosity. The distribution of ions around the particle is considered as dependent upon the distribution of the different strongly hydrated ions such as those in the outside liquid which draw water from the particle and the particle shrinks. Strongly hydrated ions within the particle draw water into the particle, producing swelling and therefore an increase in viscosity. The decrease and increase in the size of the particle are responsible for the viscosity changes.

### (9) STRUCTURE

**Soil Structure and Organic Colloids.** The mechanisms by which the incorporation of organic matter can improve the soil structure are now probably understood in a general way. Geltzer first showed that the structure-improving power of added organic matter depended on its decomposability. Organic matter itself may have no effect on structure, but either micro-organisms or their products of metabolism may act as structure improvers. Fungi produce aggregates by the mechanical entrapping of soil particles by mycelium. Bacteria are only effective if they produce gum or mucus. Their effectiveness is increased by anything that increases their gum production such as a high carbohydrate-nitrogen ratio. Sucrose added to soil is an excellent soil improver in the presence of gum-producing bacteria. Since both fungal mycelia and bacterial mucus decompose in the soil, the good soil structure

they build cannot last long after the initial decomposition of the added organic matter.

Work on the influence of rotations, leys, manure, etc. on the water-stable soil structure has given results in accordance with expectations. The quantity of water-stable aggregates increases linearly with the amount of organic matter added and with increasing organic-matter content under various systems of rotation and manuring. Cultivation tends to destroy the structure, but good rotations which include the use of leys and farmyard manure can preserve a soil structure not markedly inferior to that in the virgin condition.

Humus, however, can exert its maximum effect on the structure of the soil only when it is accompanied by a sufficiency of lime. Humus in this condition is sometimes called "mild humus" in contrast with the so-called raw humus of acid peats. Mild humus is wholly favourable in its effect on the physical condition and tillage properties of soils, and is also associated with high microbiological activity.

The action of lime is due to the precipitation of the colloidal matter coating the surfaces of the crumbs. This precipitate entrains the particles and loosely cements them together. Now humus is, in normal soils, a constituent of the hydrophilous coating of the crumbs, and in conjunction with lime it facilitates the flocculation or aggregation of the soil particles. The beneficial effect of humus on the soil structure, is therefore, dependent upon the presence of lime or some agency whereby humus is kept in the coagulated or gel form. In the absence of sufficient lime, the humus alone may even have an opposite effect upon the clay of soils, protecting and deflocculating it, and causing it to be washed downwards in the drainage water.

The chief physical defects of a sandy soil are a looseness and incoherence of the particles and an inadequate water-holding power. The binding power of coagulated humus operating in such soils will reduce the loose condition of the particles, giving body to the soil and providing better seed-bed conditions. The binding of the particles may increase rather than decrease the drainage channels through the soil, but nevertheless the coating of the soil aggregates, and the lining of the drainage channels with water-imbibing colloidal matter increases the water-holding power of the soil.

Soil structure is very important in soil classification and description. It should be noted that the most favourable type of soil structure for plant growth is the granular structure.

## CHAPTER 9

### *Minor Elements of the Soil*

BESIDES the classical elements nitrogen, potassium, phosphorus, calcium, etc. long known as essential plant nutrients, another group are now known to be needed ; these are now called minor elements, because they are needed in very small amounts only. Unless these elements are present in the soil, plants suffer from certain diseases, hitherto very obscure ; as soon as the missing minor elements are supplied, healthy conditions are established. This new aspect of plant nutrition is now being studied by agricultural experts all over the world and search is being made to discover whether any of these minor elements are missing from the soil. The work has been facilitated by the development of spectrographic and other appliances whereby very delicate tests can be carried out rapidly and effectively. Some deficiencies affect plants only and not animals, e.g. boron and apparently zinc ; others affect animals but not plants, e.g., iodine and cobalt ; and some affect both plants and animals, e.g., copper and manganese.

This whole subject of minor elements affords a striking instance of the intimate connection between pure and applied science. Nothing should be more practical than the task of finding a remedy for these obscure diseases of plants and animals which have caused serious losses and which have so long defied all efforts to cure. On the other hand, nothing could appear more abstruse and remote from practice than the highly academic investigations into spectroscopy that led to the development of the spectrograph. Yet it was the spectrograph that showed the remedy for the sheep disease in Australia and it greatly facilitated the study of all these minor elements and the part they play in soil fertility.

The elements are commonly referred to as "rare," "trace," or "minor," elements. None of these terms is entirely suitable ; most of the elements are in no sense rare, they do not occur in traces

in all plants or soils, nor are the effects they produce on plant or animal development of a minor nature. There appears to be no completely satisfactory term that can be used to refer to this group of elements. The term "secondary elements" is used frequently to contrast this group with the primary group that includes nitrogen, phosphorus, potassium, and calcium. However, this use of the term is merely for convenience and is not to be construed to mean that they are of any less importance for normal plant and animal development.

Because of its complex nature, the soil commonly contains small quantities of numerous chemical elements certain of which, in suitable compounds, are necessary in small amounts for plant and animal development. Frequently, however, elements that are essential at low concentration become toxic if they are available in slightly higher concentrations. Usual soil constituents frequently occur naturally, or they may be added by man accidentally—and sometimes intentionally in controlling insects, rodents, weeds, or plant diseases—in amounts that are deleterious to plant development and to the animals feeding upon the plants. *harmful; injurious*

The actual quantities involved are frequently so minute that routine chemical procedures are not sufficiently delicate to measure amounts that produce striking effects on the plant or animal organism. Recent careful study of the effects of these elements on growth has supplied the explanation of failures in plant and animal development previously attributed to unknown causes, or, in some instances, erroneously to other conditions.

In some cases soil deficiencies are not revealed by any effect on plant growth yet the plant is not being supplied with a sufficient quantity of some elements to produce a normal healthy growth of animals feeding on it. Among examples of this is the failure of cattle to develop normally when feeding on the products of the sandy soils of Florida, which do not supply enough iron and copper, or possibly, cobalt, to the plant. In New Zealand, the lack of enough cobalt in certain soils causes the "bush sickness" of sheep. The abnormal occurrence of human goitre in parts of Switzerland and of Wisconsin, Minnesota, and Washington is due primarily to a deficiency of iodine in the soil.

**Toxicity of some of the Minor Elements.** Many of the elements occurring naturally in soils are as undesirable as some of them are necessary. Our present information leads us to believe

that selenium, thallium, fluorine, chromium, lead, and probably arsenic, are undesirable soil constituents even at the lowest concentration.

In some instances elements are added to the soil in the form of spray residue or by direct treatment as, for example, the relatively heavy applications of lead arsenate to the soil of nurseries for the control of the Japanese beetle. The addition of lead and arsenic appears to be undesirable from the standpoints of the maintenance of soil fertility and of safeguarding animal health. Variations in soil composition and reaction cause great differences in the toxicity caused by these elements, which will be explained later under the descriptions of the effects of the two elements in question. Copper and sulphur are frequently added to the soil in the form of spray residues. The quantities of both these elements added per acre are comparatively small and except in extreme cases would be beneficial rather than harmful. The long-continued use of sulphur without liming would, however, cause a considerable rise in soil acidity and result in the depletion of the soil bases.

**Chemical fertilizers and Minor Elements.** The commercial fertilizers applied to obtain larger yields are for the most part comparatively pure salts, which through the phenomena of base exchange tend to displace the secondary elements in the soil and cause them to be used by growing crops or carried away in the drainage water. These commercial fertilizers are different from farm yard manure in that they do not ordinarily contain enough of the secondary elements to be of any significance. It is not unreasonable to believe that some small part of the increased yield following the application of commercial fertilizers is due to the increased availability of the secondary elements rather than entirely to the nitrogen, phosphorus, and potassium applied.

There is a tendency at present to use very concentrated salts as fertilizers to reduce carriage and application costs. With the use of these concentrated fertilizers the depletion of the elements not supplied may be more rapid. Most pronounced in this direction will be the depletion of the sulphur, magnesium, and calcium reserves in the soil. Heretofore very little attention has been paid, in the fertilization of lands, to sulphur and magnesium. The reason for this is that potash salts and superphosphate, which are the common constituents of many commercial fertilizers, frequently contain magnesia and commonly calcium with more sulphate than

phosphate. Thus a deficiency of calcium, sulphur, and magnesium has not occurred as generally as would otherwise have been the case.

While the continuous use of chemical fertilizers tends to deplete the essential elements not supplied to the soil, the use of stable manure, leafmould, wood ashes, and peat tends to conserve them. On dairy farms, a large part of all elements is returned to the soil, and the secondary elements contained in such concentrates as are purchased from the outside are, therefore, actually added to it. Leaf litter, leafmould, and wood ashes contain many of the elements taken from the forest soil in proportions desirable for the nourishment of the trees. The undesirable ones have been largely eliminated. Furthermore, the secondary elements in leafmould, particularly manganese, are in a very available form. In long-continued experiments at Woburn and Rothamsted it has been found that stable manure has maintained the fertility of the soil over much longer periods than has the use of chemical fertilizers containing nitrogen, potash, phosphorus, and sulphur. The numerous chemical elements contained in the manure are undoubtedly an important factor in this observed maintenance of fertility.

It should be mentioned here that Chilian nitrate of soda is the only chemical fertilizer which contains more than thirty minor elements. This is due to the fact that Chilian nitrate is not altogether an artificial fertilizer. It is manufactured from the natural deposits of "Caliche" in South America. It is in fact a natural product which is rich in iodine and borax and contains on the whole more than thirty other elements in minute quantities, some of which are known to be essential for plant growth. It is sometimes claimed that this gives special importance to Chilian nitrate of soda in contrast with other commercial nitrogen fertilizers.

Deficiencies of the secondary elements, except iodine in special cases, are not likely, however, to occur in soils formed from the decomposition of granite and other igneous rocks. These soils contain a great variety of minerals in the sands and silts, and also generally contain a relatively large amount of fine clay—the soil-absorption complex, which has the property of retaining many of the elements in a form not readily washed out by percolating water but still available to plants.

The minor elements in soils include :—

- |             |              |
|-------------|--------------|
| (1) Arsenic | (14) Lead    |
| (2) Barium  | (15) Lithium |

(3) Beryllium	(16) Magnesium
·(4) Boron	·(17) Manganese
(5) Bromine	·(18) Molybdenum
(6) Caesium	(19) Nickel
(7) Chromium	(20) Radium
(8) Sulphur	(21) Rubidium
(9) Iodine	(22) Selenium
·(10) Cobalt	(23) Strontium
·(11) Copper	(24) Thallium
(12) Gold	(25) Vanadium
·(13) Iron	·(26) Zinc

**Arsenic.** In soils in general there is no relation between the quantities of total and water-soluble arsenic. The quantity of water-soluble arsenic in natural soils and in soils to which arsenates have been added is dependent upon two things—the reaction of the soil and the quantity and nature of the clay or colloidal matter. The addition of small quantities of arsenates to acid sandy soils will give rise to such a high concentration of water-soluble arsenic that legumes will not grow. Larger applications of soluble arsenic fail to inhibit the growth of legumes on heavy soils, especially if the clay of such soils contains an abundance of iron. In some American orchards, it has been found that arsenic has not been leached below the depth of ploughing in some 20 years.

Some pot experiments indicated that 0·01 per cent. of As in the soil is harmful, and that flax is especially sensitive to As in the soil, showing an unmistakable stunting with 0·03 per cent. of As.

**Barium.** In small amounts barium is present in all soils and in all plants. Quantities present in soils vary from a few thousandths of 1 per cent. to as much as 3·68 per cent. of barium oxide (BaO) (in a special soil in the vicinity of a barite mine). Only small quantities find their way into plants; tobacco has been found to contain as much as 0·15 per cent. and lucerne 0·14 per cent.

Barium is poisonous to plants at low concentrations. In the presence of calcium carbonate, however, considerable concentrations may occur in the soil solution without rendering the soil markedly infertile. Barium replaces other bases in soil colloids very energetically. For this reason nearly all soils contain small quantities of exchangeable barium notwithstanding the fact that there is a low concentration of barium in the earth's crust. In some soils

there is so much exchangeable barium that it would seem to interfere with the absorption of sulphate by the plants through the formation of insoluble barium sulphate.

The quantities of barium taken up by the plant even from a soil high in barium are so low that there is little likelihood of animals being poisoned by eating the plant. The cattle poisoning in certain Colorado pastures that was once thought to be due to barium has since been found to be due to alkaloids or to selenium.

**Beryllium.** This has been found in small quantities in plants growing on the island of Elbe in soils containing beryl. It has also been found in spectroscopic traces in the ash of hickory leaves growing on ordinary soils.

The characteristic beryllium mineral is beryl. That this mineral is very resistant to decomposition by the soil-forming processes is proved by the high content of beryl in soils formed from pegmatite veins. Small quantities of beryl are widely distributed in granites and it is probable that granite also contains small quantities of beryllium in other forms. It would seem that clay from granite soils should generally contain some beryllium, but this has not been demonstrated. Beryllium so much resembles aluminium that it is most difficult to determine small quantities of one in the presence of large quantities of the other.

Beryllium in very low concentrations is toxic to citrus cuttings in solution cultures.

**Boron.** The determination of boron in soils presents certain difficulties, and neither its combinations nor its actual content has been studied to any great extent. Askew, Thomson and Kidson found in New Zealand soils quantities of boric acid ranging from 0.15 to 2.20 p.p.m. Terlikowski and Nowicki found that the boron content of Polish soils varied from 1 to 14 p.p.m. Bobko found that the boron content of Russian soils varied from 0.11 p.p.m. in red soils to 0.27 p.p.m. in chernozems, the amount of water-soluble boron showing a tendency to diminish with an increase of leaching in the soils. Experiments showed that peats and soils were incapable of fixing boron.

Naftel comments on the recent rapid growth in the agricultural literature of boron : between 1857 and 1900, 18 papers were published ; between 1930 and 1936, 100 papers ; and from 1936 to 1938, 350 papers were noted.

Boron deficiency in soils is suggested by Dennis and O'Brien

to be of two kinds, primary and induced. The primary kind occurs on soils derived from the weathering of igneous rocks poor in boron. The induced or secondary kind occurs in soils where there is a sufficiency of boron for plant growth, but its effect is masked by secondary factors controlling the availability of boron to plants. The most important of the factors are the lime and water content of the soil.

Heart rot of sugar beets, being noticeably more severe on soils with a high pH, was formerly assumed to be directly caused by excessive alkalinity. Brandenburg showed that heart rot could be prevented in water culture by adding 0.5-0.7 mg. of boric acid to one litre of nutrient solution. Scharrer and Schropp carried out a series of pot experiments with sugar beet. The addition of 10 g. of  $\text{CaCO}_3$  to 14-19 kg. of soil increased the tendency to heart rot, which was counteracted by addition of boric acid to the limed soil.

Brenchley and Thornton found that in the absence of boron the symbiosis between nodule bacteria and the higher plants was disturbed. They showed that the development of the nodule depends on the transport of carbohydrates, which in turn depends on the presence of a trace of boron, without which the vascular strands of the nodule cannot form.

The incidence of boron deficiency in any given crop depends not only on the amount of boron present in the soil, but also on a number of supplementary factors, such as the plant species, soil reaction and soil moisture. With regard to boron requirements, plants appear to vary greatly. Different species contain very different amounts of boron per unit of dry matter. Root crops have been long known to respond more readily than cereals to boron while legumes occupy an intermediate position. Bertrand analysed various plants grown in the same soil, the amounts of boron in the different plants varying from 2.3 mg. per kg. of dry matter in barley to 94.7 in poppies.

A third factor which effects the occurrence of boron deficiency is soil moisture. Deficiency diseases are most prevalent in dry years, but, according to German workers, the distribution of rainfall during the growing season is of more importance than the total precipitation. Meyer-Hermann found that if a very rainy spring, in which young beet develops quickly and luxuriantly, is followed by a dry spell during the summer, a severe attack of heart and dryrot may be expected. This may be partly due to the possibly higher

boron content of clays, but the greater water-holding capacity of heavy soils may also be a factor in making the boron available to plants.

**Bromine.** Bromine appears to be generally present in quantities of the order of a few parts per million in plants and soils. Raw German potash salts contain considerable bromine. This element supplied to plants in the form of sodium bromide shows no immediate ill effects, but later in the life of the plant the effect is quite serious. The clay of ordinary soils does not retain bromide and it would be quickly leached from the soil.

**Caesium.** This rare alkali has been reported in a few plants and soils in spectroscopic traces. Beyond these facts there is very little known about caesium in relation to plant growth. The caesium mineral pollucite occurs occasionally in pegmatite veins and there is a possibility that in rare cases soil masses contain notable quantities of caesium. It behaves much like potassium, and like that element it is probably absorbed and retained in the soil clay. Although this element resembles potassium it cannot be substituted for potassium to produce normal plant growth.

**Chromium.** Chromium salts and particularly chromates are very toxic to plants. The quantities of chromium in most soils and plants is infinitesimal, but soils formed from serpentine and other ferromagnesian rocks may contain appreciable quantities. These soils are usually infertile owing, according to Robinson, Edgington and Byers, to their content of chromium and nickel.

**Sulphur.** Evidence that tea-yellows was caused by a deficiency of sulphur was obtained from replicated manurial experiments, which indicated that the disease was effectively controlled by fertilizer applications only when sulphur-containing fertilizers were used. Effective treatments included applications of the sulphates of potassium, sodium, ammonium and manganese, and elementary sulphur. The soils were lateritic and contained, on the average, 0.031 per cent. of sulphur, i.e., within the range normally encountered in soils. Tea-yellows symptoms were also produced in sulphur-free water cultures. Analyses of plant material showed that healthy leaves contained appreciably more sulphur than diseased leaves, but in this connection Storey and Leach state that the method of sampling the analysed material was open to criticism.

The disease usually appears in soil which has been impoverished by rainfall or cropping, but on certain types it may appear in young

plantations on newly cleared land. It decreases in severity during the months of the heaviest rainfall.

Rice at the Mandalay Agricultural College farm suffered from a condition in which the plants turned yellow and remained stunted. The application of chemicals containing the sulphate radical, e.g., ferrous and copper sulphates and sulphuric acid, caused the plants to regain their green colour, and, when treated sufficiently early, to attain a normal healthy condition. Ferric chloride, sodium chloride, manganese chloride and ammonium nitrate had no effect on the chlorotic plants. It is suggested that the trouble may be caused by a lack of sulphur in the soil.

**Iodine.** Chatin (1840) established that all arable soils contain some iodine, and a large number of soil analyses has since confirmed this observation. The amount of iodine found in soils ranges from 0.6 to 6.0 p.p.m. though amounts outside these limits have been reported. Soils from England and Scotland contained from 2.4 to 8.0 p.p.m. of iodine; two soils from Kenya 3.0 to 3.5 p.p.m., and one from the Falkland Islands 25.0 p.p.m. Australian soils contained 0.7 to 9.6 p.p.m. with an average of 3.53. New Zealand soils had an average content of 8.22 p.p.m., varying from 1 to 24 p.p.m. It is suggested that the soils from the Falkland Islands and those of the New Zealand group which contain large amounts of iodine, owed their accumulations to the excreta and debris from flocks of sea birds which inhabit these islands. Japanese soils contained from 0.49 to 56.5 p.p.m., most of the soils containing 1 to 3 p.p.m. of iodine. The largest amounts were found in older Quaternary material. Soils of pH 6.5-7 contained more iodine than do more acid soils. Clay soils had the highest average content and sandy soils the lowest.

McHargue and Young found that soils derived from limestone strata in Kentucky contained the largest quantities of iodine while those derived from sandstone strata contained the smallest. The high iodine content of soils from limestone is due, it is suggested, to the weathering of limestone strata from the surface, leaving iodine compounds which resist weathering.

Scharrer, studying the iodine content of South German soils, found no connection between iodine content and pH or total acidity. Sandy soils had the lowest, clay soils higher, and peat soils the highest iodine content. In general high iodine content was associated with abundant colloids and organic matter.

Balanescu found that the iodine content of soils from different districts of Rumania varied from 20 to 200 gamma per kilogramme.

Smolik found no correlation in Czechoslovakian soils between the iodine content of soil and that of the parent rocks. The maximum amount of iodine in the soil profiles was in the surface layer.

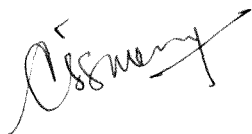
Fellenberg drew attention to the higher content of iodine in soils than in the rocks from which they were derived, and ascribed this to the absorption of iodine by plants and its subsequent return to the surface soil. Absorption of iodine by weathered rocks and mineral soils was stronger when the reaction was acid than when it was basic. Bleyer and Stoklasa noted that moor soils which are highly acid are relatively very high in iodine. Scharrer and Schwaibold stated that iodine tends to be leached out of soils deficient in clay colloids and humus.

Hercus, Benson and Carter found that iodine was abundant in soils derived from igneous rocks, and deficient in alluvial soils which had been subjected to constant leaching. On these latter soils goitre was endemic.

High incidence of goitre is usually but not invariably associated with a low iodine content of the soil. The occurrence of goitre on certain geological formations, principally on deposits rich in calcium and magnesium, had been observed prior to the formulation of the iodine-deficiency theory. The literature on this subject has been reviewed by Hercus, Benson and Carter who showed that goitre was frequent on calcium-rich formations and absent from formations such as granite and basalt. Not all calcium-rich areas, however, are goitre areas.

**Cobalt.** Bertrand and Mokragatz found cobalt to be present in all soils. It does not seem to be an essential plant nutrient and it is impossible to discover cobalt deficiency in the soil by any effect on plant growth, but the amount of the element absorbed from the soil by the herbage may be insufficient to produce normal healthy growth of grazing animals. In New Zealand soils low in cobalt were also found to be low in other plant foods, and lime and phosphate had to be added before cobalt additions proved satisfactory.

Cobalt was found to decrease in pastures under drought conditions. It also decreases in spring and summer with maximum growth of the plants, and increases in late autumn and winter. Some healthy pastures contain 0.04 p.p.m. to 0.37 p.p.m. or more, bush-sick pastures between 0.005 p.p.m. and 0.17 p.p.m. of the dry matter.

A handwritten signature in cursive script, likely reading 'A. S. M. J.', is written in the bottom right corner of the page.

An association of cobalt in soils with magnesium in the parent rocks has been found in New Zealand, Cornwall and the Scilly Isles. In New Zealand certain soils derived from magnesium-rich rocks contained over 300 p.p.m. of cobalt, while soils derived from rocks containing little magnesium (e.g. granite) had cobalt contents from 0.4 to 1.8 p.p.m. Dartmoor soils over granite on which pining disease occurs contained 2.8, 3.0 and 3.7 p.p.m. Soils from healthy fields and derived from Devonian shales contained 11, 18, and 13 p.p.m.

Other soils examined by Kidson included highly leached soils from rubber estates in Malaya with extremely low cobalt contents and samples of an "Ilepa" soil from Nigeria with a marked concentration of cobalt (110 p.p.m.) in a concretionary horizon rich in iron. Nyasaland soils contained 15, 16 and 27 p.p.m. and a typical red earth from Batum, U.S.S.R. derived from andesite contained 35, 27 and 62 p.p.m. in the A, B, and C horizons respectively.

**Copper.** This has been found in most agricultural soils which have been examined for it, in amounts up to 140 p.p.m., but 20 p.p.m. appears to be a usual upper limit. Soils treated with copper sprays (e.g., Bordeaux mixture) may of course contain larger amounts, and also soils from copper-mining areas.

Numerous instances have been recorded in which pathological conditions in plants have been cured, and others in which yields of healthy plants have been greatly increased, by applications of copper to the soil. There is evidence that copper may function both as a soil stimulant (catalyst) and as a plant nutrient.

Reclamation disease is most common on heath soils which possess a high capacity for fixing copper in an unavailable form, as evidenced by the fact that doses of copper sulphate that would be lethal to plants on other soils can be applied to heath land without harm.

Meijer concluded, as a result of several years' experimental work, that the amount of copper sulphate which could be applied with safety was related to the humus content of the soil. Soils containing 7 per cent. of humus or over might be given 100 kg. per hectare, whereas on sandy soils with little humus even 50 kg. per hectare might be too much.

Amdt and Segeberg, on the other hand, assume that copper added to peat soils transforms the physical condition of the organic colloids in such a way as to increase the amount of available water—

in other words they believe that reclamation disease is essentially a water-deficiency phenomenon. They assume that copper sulphate flocculates the organic colloids and thus keeps the capillaries open when the humus dries out, so that water can be brought up from the lower horizons. A further effect of copper sulphate is to precipitate copper humate which, according to the authors, forms a permeable coating round the humus particles and makes them more easily wetted. Kwiecinski also assumed that the action of copper on plants was indirect, certain favourable reactions being stimulated as a result of a change in the colloid structure of the soil.

Dippel considers Cu and Fe as oxidation catalysts for the transformation of phenols into dark-coloured products. Protein-degradation products, lignin, tannic acid, and substances from micro-organisms are sources of phenol derivatives.

The oxidizing-catalyst hypothesis has been elaborated by Willis and Piland who affirm that an important function of copper is the regulation of the oxidation-reduction potential of the soil. The chief reducing agent in the soil is the organic matter and the chief oxidizing agent is oxygen, but reduction and oxidation only take place in the presence of activators. Reduction is activated by microbiological activity (and depends therefore to some extent on pH); oxidation can be activated by a number of catalysts of which copper may be one. In organic soils the oxidation-reduction equilibrium tends to be well over on the reducing side unless an oxidizing catalyst is present. Organically-combined iron, which is always present in such soils, does not appear always to catalyse oxidation sufficiently to balance the reducing processes and is liable to accumulate in the ferrous form in sufficient quantities to be toxic to plant growth. Willis has obtained evidence of a "copper-iron antagonism" in plants, shown by a reduction in their iron content when grown on soils or in culture solutions to which copper has been added. It is assumed that this antagonism works by copper oxidizing soluble ferrous iron, thereby lowering its availability to plants.

It is possible that the chief function of copper, both in the plant and in the soil, is that of an oxidizing catalyst; when deficient in the plant, it affects the health, and when deficient in the soil, the yield of the crop. The greatly increased yields which have been obtained by copper applications might then be explained by an enhancement of the oxidation processes in the soil rather than by the removal of an actual copper deficiency.

**Gold.** This is widely distributed in nature, mostly in very minute quantities. It has been reported that sands from the banks of the river Danube in South Slovakia contain about 0.1 gram of gold per ton, and plants growing on this sand are able to accumulate gold. The ash of corn grains contained 0.0002 per cent., and the ash of Clematis contained 0.06 per cent. gold. The whole plant of scouring-rush accumulated gold to the extent of 610 grams per ton of ash. The metal is said to be concentrated in the seeds of the flowering plants.

**Iron.** Chlorosis caused by iron deficiency is chiefly found on soils rich in lime or manganese which appears to immobilize the iron, and thus to produce a condition of deficiency. Lime-induced chlorosis of fruit trees has long been treated by direct application of iron to the plant. Among the more susceptible trees are pear, apple, quince, peach, apricot, prune, plum, cherry, walnut, orange and lemon. Raspberries also suffer severely.

Gile showed from a series of analyses that a relationship existed between the incidence of pineapple chlorosis and the presence of calcium carbonate in the soil. The highest content of calcium carbonate found in any soil producing healthy plants was 1.15 per cent., the lowest found in soils producing chlorotic plants was about 2 per cent. (a loose sandy soil). Analyses showed the chlorotic plants to have a lower nitrogen content and less peroxidase than green plants. Treatment with iron increased both the nitrogen and peroxidase content.

Triwosch has shown that a similar chlorosis is produced by manuring yellow lupins with magnesium carbonate, the injury increasing with the amount of magnesium up to 0.2 per cent. of magnesium in the soil. Both magnesium—and lime—induced chlorosis of yellow lupins can be cured by application of iron. Triwosch found that the amount necessary bore some relation to the amounts of the alkaline earths present in the sand cultures which he used.

Johnson states that manganese and calcium carbonate can each exert an additive chlorotic effect in the presence of the other. He draws attention to the fact that iron in the ferric state is unavailable to plants on a great variety of soils since it remains completely precipitated even in quite acid solutions, and becomes available only when reduced to the ferrous form. On calcareous soils, chlorosis does not occur in the presence of plenty of organic matter or other material capable of furnishing a supply of ferrous iron.

Johnson's explanation of manganese chlorosis is that in soils containing an excess of manganese dioxide the iron is kept oxidised to the ferric form, and consequently is not sufficiently available to plants susceptible to chlorosis. Any iron which is added to the soil is also immediately rendered unavailable.

He considers that the two main factors affecting the availability of iron in the soil are (1) the reaction, and (2) the relative amounts of oxidizing or reducing agents in the soil, that is, the same factors as affect manganese availability. When the soil pH is over about 4.5 ferric iron is largely unavailable to plants sensitive to chlorosis, and the chief source of iron is ferrous salts. The manganese dioxide present in the Hawaiian soils appears to keep the iron oxidized to the ferric form and unavailable, although these soils may run as high as 25 per cent. ferric oxide. Heavy applications of sulphur have had no effect in checking chlorosis.

Monnier and Kuczynski state that the iron normally present in the soil is insoluble. Iron compounds placed near the roots had a marked effect on plants, but placed elsewhere they were rendered insoluble before they could be absorbed. Tottingham and Beck consider that manganese-induced chlorosis may be caused by manganese interfering with the role of iron in the production of chlorophyll.

**Lead** in very small quantities is of general occurrence in plants and soils. Normally the quantities in edible plants or parts thereof are so small as to have no effect on the health of the animal eating the plant. However, the accumulation of lead in the soil from spray residues may be of sufficient magnitude in some soils to raise the lead content of food plants to a dangerous point. Lead is a cumulative poison, and small quantities that by themselves cause no harm become dangerous when taken constantly.

Lead is "fixed" by the clay of the soil, and it would appear that the sulphate, sulphide, phosphate, and carbonate ions should render lead added to a normal soil so insoluble as to be inactive. Very acid soils, however, would increase the solubility of the lead. In some Oregon orchard soils it has been found that lead has not been carried down below the plough depth after the orchards had been sprayed for 20 years with lead arsenate.

Soluble lead compounds are toxic to plants except in very low concentrations, at which, in some cases, they seem to have stimulated growth. In some commercial apple orchards the residues from lead

arsenate sprays have accumulated to such an extent that green manuring crops can no longer be grown. It is supposed that arsenic is chiefly responsible for this condition, though lead may be a contributing cause.

**Lithium** occurs in plant ash almost universally but in very small quantities. In soils the quantities present have been found to vary from a spectroscopic trace to over 100 parts per million in ordinary agricultural soils.

Some field experiments show that very small applications of lithium salts are frequently stimulative ; larger concentrations have proved toxic. Tobacco and potatoes are less susceptible to injury by lithium than many other crops. Lithium when applied in any considerable quantity to the soil in the form of soluble salts produces toxic effects on tobacco resulting in well-defined spotting of the lower leaves.

Many lithium minerals occur in pegmatite veins. Since these characteristic lithium minerals appear to alter or weather easily, it is doubtful whether many soils will contain more than a trace of this element. Tourmaline, however, which may contain as much as 1.5 per cent of lithium, is quite resistant. Lithium appears to act in the same manner as sodium toward the soil colloids and is not absorbed like potassium.

**Magnesium** is sometimes a "major" element in soils. Soils derived from serpentine may contain 30 per cent. and more of magnesium. Alkali soils in which the predominant exchangeable base is magnesium have been reported from the United States, Canada, Russia and Hungary. Normal soils of humid regions, however, contain only a fraction of one per cent. Brioux states that the magnesium soluble in strong acids varies in French soils from 0.016 to 0.028 per cent. in alluvial soils ; from 0.11 to 0.16 per cent. in siliceous clays ; and from 0.5 to 0.6 per cent. in calcareous Seine alluvium. The "available" magnesium was very low (0.0001-0.0004 per cent.) in sandy soils, but reached 0.01-0.03 per cent. in heavier soils. Bastisse found the magnesium content of most heavy French soils lay between 0.3 and 0.6 per cent., of which 70-90 per cent. was soluble in strong acids. The exchangeable magnesium was only a small fraction of the total and usually varied between 0.015 and 0.045 per cent. of the soil. That these quantities of magnesium may be insufficient for plant nutrition is shown on the one hand by the significant yield increases sometimes obtained by applying



magnesium fertilizers, and on the other by the appearance of deficiency symptoms which can be corrected in the same way.

Numerous experiments carried out in Germany with magnesium fertilizers have given conflicting results, partly due to the fact that little or no attention was paid to the magnesium contents or requirements of the soils investigated. It may be assumed that many of the soils were adequately supplied with magnesium from the beginning. As yet, however, there are no reliable methods of estimating the adequacy of the soil magnesium supply, though Niklas and Poschenrieder claim to have obtained satisfactory indications by means of the *Aspergillus* test. Ramann gave the arbitrary figure of 0.25 per cent. as the lower limit for a sufficient content in the soil to produce maximum yields. Brioux obtained some evidence in field experiments of a magnesium effect in soils containing up to 0.03 per cent. of available magnesium.

Magnesium compounds are mostly soluble and are readily removed by leaching, consequently indications of magnesium deficiency are usually found on light, well drained soils in humid regions. The use of potash fertilizers and lime under certain conditions may cause magnesium-deficiency symptoms to appear in crops. Garner found that additions of sulphur aggravated magnesium deficiency in tobacco.

As might be expected deficiency of magnesium—a component of the chlorophyll molecule—is always manifested by defective foliage, the commonest symptoms being chlorosis, necrosis of interveinal tissue and premature fall of the older leaves. The lower leaves are the first affected. In plants such as grasses and cereals in which the leaf veins are parallel, chlorotic strips of interveinal tissue alternate with green veins and the leaves develop a streaky appearance due to a loss of chlorophyll between the veins at the leaf tip and margin.

Leaching seems to be the simplest explanation in most of the recorded instances of magnesium deficiency. Bastisse found three times as much magnesia in the subsoil as in the surface. Auten, comparing the surface soil of 17 different forests and adjacent cultivated plots, found considerably less magnesium in the cultivated than in the forest soils. The reverse relationship was found in the subsoils, suggesting that loss of magnesium from the surface soil takes place through leaching and erosion. The fact that deficiency symptoms have been observed most frequently on light, acid soils

suggests that they are caused by a true lack of magnesium in the soil rather than by conditions rendering the element "unavailable." Magnesium is one of the most easily soluble and most weakly absorbed of the common exchangeable cations, and actual deficiencies in soil may be much more widespread than has yet been recognized.

**Manganese.** The amount of manganese found in soils is very variable, the range in surface soils of the United States being from less than 0.001 per cent. to 1.27 per cent., while some tropical soils contain as much as 15 per cent. The manganese content is usually highest in the surface soil. It reaches a minimum in the B horizon and generally increases in the C horizon. In soils containing a layer of calcium carbonate below the surface, deposits of manganese dioxide are often found just above the layer. Manganese dioxide is found in the sand, and especially in the silt, but scarcely at all in the clay or colloidal fractions of soil.

A certain amount of the soil manganese occurs in some ferromagnesian minerals and other complex silicates. Some of these are extremely insoluble. Manganese has been shown to be one of the most easily exchangeable bases, particularly under acid conditions.

Kelley and McGeorge found that manganese compounds are made much more water-soluble by heating the soil sufficiently for them to be reduced by organic matter. Steam-heating soils for three hours at 240° F. greatly increased the concentration of manganese in aqueous extracts. The amount of manganese in plants grown in steamed soils was much larger than in unsteamed soils. Samuel and Piper greatly increased the solubility of manganese of two soils by heat sterilization.

The earliest record of the occurrence of manganese in plants was made by Scheele, who discovered the presence of manganese in aniseed. In 1872, Leclerc published analyses of various plants and soils and concluded that manganese was a universal constituent of soils and a common constituent of plants. McHargue, following up Bertrand's pioneer work on the physiological importance of manganese, showed that it was an essential element for plants. Further evidence to this effect was obtained by Samuel and Piper.

The manganese requirements of plants vary considerably. Leclerc's investigations showed that certain forest trees, particularly the firs, birches and elms, contained rather large amounts while herbaceous plants contained only small amounts.

The manganese contents of certain food crops are given by Richards as follows :—

TABLE 12

*Manganese content in mg. per 100 g. of dry matter.*

Lettuce ... ..	13.3	Beetroot ... ..	2.17	Potato ... ..	1.43
Pastures ... ..	12.17	Barley ... ..	1.85	Wheat ... ..	7.88
Spinach (Kenya)	8.9	Carrots ... ..	1.67	Leek ... ..	0.44
Oats, whole ... ..	5.6	Cabbage ... ..	1.50	Turnip ... ..	0.36

Bertrand in France, and several investigators in Japan, started a vogue for so-called catalytic fertilizers containing manganese which, besides having a somewhat uncertain effect on the yields of various crops, were of value in controlling "grey speck" of oats in North and Central Europe. But it was not realized that this effect might be due to manganese deficiency. Sohngen first suggested that grey speck was caused by manganese deficiency in the plant. Samuel and Piper during an investigation into the cause of "road take-all" of oats in Australia, found that the symptoms of the disease were identical with those of grey speck and those obtained by omitting manganese from different culture media.

The Mn requirement and tolerance of plant species vary considerably. The uptake of Mn is influenced by soil-pH and fertilizer treatment. The available Mn in soils is inversely related to pH. Liming of acid soil to pH 6.0 lowered the level of intake of Mn by plants to that obtaining in soils of pH 8.0. Application of superphosphate increased the Mn intake of maize. Available and replaceable Mn contents of soil are affected more by pH than by the exchangeable base content.

G. D. Sherman found that neutral and alkaline conditions favour the formation of the manganic ion, and acid conditions the manganous ion. Strong reducing agents are capable of reversing the oxidative equilibrium. Winter conditions favour formation of the manganous, and summer conditions the manganic ion. The nature of the organic matter and the clay content also are influential factors.

As already stated, manganese-deficiency symptoms usually occur on soils of high pH value and in the presence of considerable amounts of organic matter. Various hypotheses have been put forward to account for the effect of these conditions in rendering manganese

unavailable, but although several of them offer a reasonable explanation of the effect of liming on the unavailability of manganese they do not appear to account for the part played by organic matter.

Pipe, Conner, Steenbjerg and other writers consider that the availability of manganese in soils is related to the oxidation-reduction equilibrium and to the soil reaction. Steenbjerg also associated availability with exchangeability. By successive leachings with normal magnesium nitrate he determined the amount of exchangeable manganese according to the Vageler-Woltersdorff equation :

$$y = \frac{Sx}{X + qS}$$

or  $\frac{dy}{dX} = \frac{1}{q} \frac{(S-y)^2}{S}$

where  $y$  = mg. of Mn extracted per 100 g. of soil.

$x$  = amount of leachate in units of 100 c.c.

$S$  = total exchangeable Mn in mg. per 100 g. of soil.

$q$  = a measure of the energy of absorption of exchangeable Mn by soil colloids.

High  $q$  values denote slow extraction of manganese and low availability. In some soils the value of  $q$  is the chief factor determining the availability of manganese.

Leeper found that manganese deficiency was confined to soils of pH 6.7 or more and occurred especially on heavily limed, sandy podzols. He distinguished manganese-deficient soils by leaching soils (of pH greater than 7) with a normal ammonium-acetate solution of pH 7 containing 0.2 per cent. of quinol. Only those manganese compounds which can oxidize quinol at pH 7 with reasonable speed are dissolved. Leeper calls this the "active" manganese dioxide. In deficient soils it was present in quantities containing less than 15 p.p.m. of manganese while in healthy soils it sometimes exceeded 100 p.p.m. The amount of active manganese dioxide in a soil indicates whether a soil is liable to develop manganese deficiency after liming or not.

The use of copper in the control of reclamation disease frequently causes grey speck to appear. Willis and Piland believe that the maintenance of manganese in a state of oxidation and, therefore, of unavailability depends on the presence of a catalyst such as copper. Mulder considers that although there may be some soils which are deficient in both copper and manganese, it is more probable that the

addition of copper to the soil stimulates the microbiological oxidation of manganese that has been shown to occur in gel plaques. Smith found that a few gamma of copper materially enhanced the oxidation of manganese by moulds. Oxidation, following the addition of copper, leads to the formation of manganese peroxide which is useless to plants, and thus may cause grey-speck disease.

**Molybdenum** is the latest addition to the list. Its action is certainly complex. In very minute quantities it is claimed to be necessary for plant growth. Ferguson, Lewis and Watson have shown that molybdenum is present in the "teart" herbage of Somerset and Worcestershire (England) in considerably larger amounts than in the normal fields close by. Teart herbage, when fed to cattle causes a failure of milk, loss of condition and sometimes death. Sheep are also affected, but not horses. Cattle fed with molybdenum in amounts equivalent to those found in the fodder developed the same pathological conditions. Teart pastures are associated with Lower Lias formations. Soils derived directly from the Lower Lias are naturally rich in molybdenum (up to 0.01 per cent.), contain free calcium carbonate, are alkaline in reaction and very teart. Molybdenum is not easily absorbed by plants from acid soils, and acid soils indirectly derived from the Lower Lias are much less teart if at all.

Several investigations on the teart pastures indicated that close texture and lack of drainage might be predisposing factors. Healthy land never became teart, but the reverse occurred frequently when drainage and cultivation had been in progress for several years. Teartness is worst during moist autumn months, is rare in very dry seasons, is destroyed by frost, and is reduced as the herbage becomes mature.

**Nickel** is present, generally in minute quantities, in all soils and probably in all plants. The comparatively recent discovery of a specific organic precipitant for very small quantities of nickel dimethylglyoxime, has made it possible to determine minute quantities of this element with accuracy.

Several soils derived from ferromagnesian rocks have been found to contain nearly 0.5 per cent. of nickel oxide. The quantities found in normal soils, however, will range from a few parts per million to a few thousandths of 1 per cent. Plants seldom contain more than 2 or 3 parts per million.

In all but the most minute concentrations, nickel is toxic to plant

growth, and the waste from mines where nickel ores are crushed have been the cause of serious complaints from neighbouring farmers.

Nickel would appear to be one of the causes of infertility observed in soils formed from high ferromagnesian rocks. From an agricultural standpoint, nickel may be considered a deleterious element. No deficiency diseases are now known to be due to a lack of nickel. All soils, with the possible exception of very sandy leached soils, should contain enough of the element to supply plant needs.

**Radium.** Considerable work has been done on the effect of radium on plant growth. While some stimulation in growth has been reported as resulting from the application of radioactive wastes to soils, the consensus of opinion is that such applications are without desirable effect. Applications of radioactive residues increase the radioactivity of the soil to an inconsequential degree compared with the natural radioactivity, so that no increase in yield could be expected.

Exposure of seed to radium emanations, if not continued too long, hastens the maturity of the plant after germination. Some commercial success has been obtained by treating sweet corn with similar emanations from electrical sources for regions in which the growing season is short.

**Rubidium** closely resembles potassium and probably enters into much the same reactions in soils and plants as that element.

Rubidium can be detected spectroscopically in all soils and in all plants. The quantities present run from spectroscopic traces to several hundredths of 1 per cent. Soils developed from pegmatite veins may contain relatively large amounts of rubidium, and on such soils plants will contain considerable quantities of this element.

Rubidium is probably absorbed by the colloidal matter of the soil and held against leaching even more tenaciously than is potassium. Thus, it is probable that even the small quantities of rubidium that may be present in the original rock will persist in the clay or colloidal matter formed from the rock.

In small quantities, rubidium has been found to be stimulating to plant growth, but it does not seem to be able to replace potassium.

**Selenium** is the only mineral element known to be absorbed from the soil by food plants in sufficient quantities to render them lethal to animals. It has been shown to be the cause of "alkali disease" of livestock that has been known for many years in South Dakota, U.S.A., and adjacent regions and is characterized by loss of

hair and hoofs, lameness, liver lesions, and oedema. Cattle, horses, pigs and poultry are affected. The effect on poultry is to reduce the hatching power of eggs and cause deformity in the embryos.

Experiments at the South Dakota Experiment Station traced the trouble to the grain in the diet of affected animals. In 1928 a series of investigations begun by Franke showed that the disease was produced by consumption of grain and other vegetation grown upon quite well-defined soil areas. In 1931, following a suggestion made by H. G. Knight, a sample of toxic wheat was analysed and shown to contain from 10 to 12 parts per million of selenium. From a reconnaissance survey in 1931 of an area known to be affected, it was found that the toxic vegetation occurred on soils derived from Pierre shales and that there was a wide variation in the toxicity of the vegetation both geographically and seasonally. Samples of soils were found to contain selenium. Seleniferous vegetation produced in artificially selenized soil and sand cultures caused symptoms of poisoning when fed to rats. Rats and pigs fed with inorganic selenium compounds developed the same symptoms of poisoning as when they were fed with the naturally toxic grain.

Surveys made during 1934-1936 showed that seleniferous areas in the United States are widespread. Selenium has also been found in a large number of Hawaiian soils and in a similar number from Puerto Rico. In Cuba, the only case of selenium accumulation was in a swamp soil which contained 32 per cent. of organic matter and 22 parts per million of selenium. The existence of an enormous area of seleniferous soil in Canada has been revealed by a reconnaissance of parts of Alberta, Saskatchewan and Manitoba. Selenium in shales varied from 0.3 to 3, and in soils from 0.1 to 5 parts per million. Toxic vegetation containing *Astragalus* occurred on soils derived from Cretaceous shales, and is believed to cause the stock ailment known locally as "frozen feet". Evidence was obtained that glacial soils might also be toxic.

Although it is believed that selenium is of general distribution selenium toxicity appears to be confined, to arid and semi-arid regions. No soils containing selenium in humid or irrigation areas have been found to produce toxic vegetation.

Selenium may be present in soils in three forms which become available to plants only by slow processes of hydrolytic action. These are free selenium, pyritic selenium and basic ferric selenites. The last seems to be the more common. It also may be present in forms

immediately available to plants as selenates and as more or less evanescent organic compounds probably of the general order of amino acids. These last forms seem to be those which are subject to eluviation ; and to the removal of which, by percolating water, is to be ascribed the low content of selenium in plants grown in irrigated and humid soils even when selenium is fairly abundant in the soils.

The distribution of selenium within the soil profile varies greatly and depends on a number of factors such as the maturity, texture, chemical composition and colloid content of the soil, parent material and rainfall. Organically combined selenium is particularly mobile. The availability of selenium in soils was considered by Olsen and Moxon to be " directly dependent upon the amount of water-soluble selenium in the soil, which is evidently correlated with or dependent upon the selenium in the organic fraction or humus of the soil."

Hurd-Karrer considers it doubtful whether the reduction in absorption in presence of excess sulphate has any wide practical value for agriculture in the naturally seleniferous soil areas. The sulphur-selenium antagonism has been observed only with selenates, and selenium in naturally toxic soils is usually present in the form of selenite, and organic selenium from plant residues. Moreover, studies on the sulphur-selenium relationship deal only with selenium toxicity to plants (not to animals).

Byers and Knight found that subsurface drainage lowered the selenium content of the soil. In one case the water from a drain in operation 16 years had a small selenium content, while water from one operating for a year only had fifteen times as much (0.08 and 1.2 p.p.m. respectively). In another area of less dense soil a drain operating for two weeks only had water with 1.98 p.p.m. while a near-by drain operating for an unknown period contained 0.07 p.p.m.

Nelson, Hurd-Karrer and Robinson have issued a warning against the use of selenium compounds as insecticides, since there is considerable danger from even minute quantities of selenium in soils in which food products are grown. This problem is also discussed by Phillis and Mason, who showed that cotton plants could be rendered toxic to the cotton stainer and the pink boll worm by the application of small amounts of sodium selenate to the soil.

**Strontium** is closely related to calcium and barium. In the 10-mile depth of the earth's crust there is about 0.018 per cent. of strontium compared with 3.65 per cent. of calcium. Strontium is

widely distributed in soils, but in small quantities of the order of 0.05 per cent. Plants contain roughly one-fifth as much.

Strontium probably reacts like barium with the colloidal matter of soils. One would expect it to be adsorbed rather energetically and to displace some of the other bases present in greater quantities. Such a reaction would account for the persistence of small quantities of strontium in the soil.

Strontium does not seem to be essential to plant growth. In water-culture experiments it can only partially replace calcium in the plant. Strontium salts are toxic to plant growth in all but relatively small concentrations, but not so toxic as barium salts.

**Thallium** is poisonous to both plants and animals. Little is known of its natural occurrence in plants and soils. When artificially applied, it is probably taken up by the plant, and as little as 35 parts per million in sandy soils has practically prevented the growth of plants. Whether this element is stored in the edible parts of plants in quantities sufficient to be toxic to man and animals is a question for further research to determine.

It was recently shown that thallium occurs in soils less acid than pH 5.8 and is most common in the pH range 7.0-7.5. It responds to treatment with nitrogenous fertilizers. Bortner and Karraker, moreover, have shown that the symptoms of thallium toxicity, although similar to, are not quite identical with, those of "frenching" which they believe to be related in some way to the reaction and lime content of the soil.

**Titanium** is almost a major constituent of soils; few soils contain less than 0.5 per cent. of titanium dioxide, and some Hawaiian soils contain as much as 10 per cent. The major part of the titanium in soils seems to be of an inert nature resembling silica.

The leaves of plants contain a few parts per million of titanium, and like iron, aluminium, and zinc, titanium follows the concentration of the chlorophyll when the composition of the blanched green leaves of cabbage and lettuce are compared.

**Vanadium.** Considering the resemblance of this element to phosphorus, there is surprisingly little vanadium in plants. There is some geological evidence that in the past plants or animals have concentrated vanadium. Some Peruvian shales contain up to 0.5 per cent. of vanadium as pentoxide. Analysts have found that the ash of several peculiar samples of cannel coal have yielded values of vanadium pentoxide ranging from 35 to 38 per cent. Asphaltic sub-

stances in many localities contain considerable vanadium. The same may be said of petroleum products, and there is considerable evidence that, in past geological ages at least, vanadium has been concentrated by biochemical processes.

Vanadium is present in agricultural soils in quantities ranging from 0.01 to 0.1 per cent. In the analysis of a series of 48 plants, only 4 showed the presence of more than 10 parts per million of vanadium. These were pine needles, beets, and bean and clover plants.

Vanadium is concentrated in sandstones and other sedimentary rocks and in clays. With the soil colloids, it would be expected to behave like phosphorus.

**Zinc.** It was discovered by accident that zinc salts cured pecan rosette disease. An ordinary galvanized water bucket provided the clue. This bucket was used during the autumn of 1931, when Alben and Cole were experimenting with dips and sprays to control the rosetting of pecan trees. They were treating the trees with solutions of iron sulphate. Some of these solutions were placed in wood buckets, and trees treated with solutions from these buckets did not respond as readily as when they were treated with the same solutions contained in the galvanized iron buckets. It was conjectured from this that some of the zinc in the galvanized coating might have been removed, and experiments were then begun with zinc sulphate. This gave almost immediate success. They then experimented with zinc sulphate added to the soil, sprayed on the leaves, as hypodermic injections into the tree trunks, and by other methods. All were apparently successful.

In California the effectiveness of zinc was also discovered accidentally. In experiments with apple rosette, iron sulphate applied as a fertilizer was successful in controlling the disease, but the beneficial results were traced to one per cent. of zinc found, on analysis, in the ferrous sulphate as an impurity. Chemically pure ferrous sulphate was ineffective. Further experiments showed that zinc sulphate cured the disease whether it was applied as a spray, injected into the trunk or applied to the soil as a fertilizer.

In California trees show zinc deficiency mainly on light soils. On heavy soils zinc deficiency rarely occurs except where there has been heavy manuring. On the corral soils zinc does not always cure the trees completely. Applications of copper with zinc, however, are beneficial. Experiments begun in 1931 with zinc sulphate gave good results. Zinc sulphate was a specific treatment when applied either

to the soil or to the tree in the form of a spray. Salts of copper, manganese, potash, magnesium and calcium as well as nitrogenous fertilizers were useless. Chicken manure, which contained an appreciable amount of zinc, was also found to be a corrective for bronzing.

In Utah, zinc-deficiency has usually appeared in fruit trees growing on non-calcareous soils ; no Zn deficiency has been observed on soils derived principally from limestone. The Zn content of calcareous soils was found to be almost twice that of non-calcareous soils, though the parent rocks contained about the same amounts of Zn ; Zn is apparently more easily weathered from silicate rocks. No consistent correlations were found between values for total or available Zn, organic matter, and pH.

The effect of zinc in preventing plant diseases, whether applied to the soil or directly to the plant, provides some evidence that it is an essential nutrient element. Chapman and Vanselow, working on mottle leaf of citrus, concluded that the results of their experiments were more in harmony with the view that zinc is an indispensable food element than that it functions as an antiseptic, or corrective.

Brenchley drew attention to the high toxicity of water-soluble zinc compounds in sand and water cultures, but a toxic concentration has seldom been found in field soils. The great divergence in the toxic limits of zinc that have been found by different workers was attributed by Baumann to the wide difference in fixing power of soils for zinc. A much lower concentration of zinc was toxic in sandy soils than in humus and marl soils, which had greater fixing power for zinc. A considerable amount of work on the behaviour of zinc in soils at the Florida Station agrees with Baumann's findings. Absorption of zinc (from the sulphate) was highest in soils of high colloid, calcium, and organic-matter contents. Jones found that a large part of the zinc added to soil is held in exchangeable form, replacing calcium. On marl and alkaline organic soils quantities of zinc are held as the humate and carbonate. Calcium carbonate applied to a Norfolk fine sand at the rate of 1,000 lb. per acre alleviated a toxic condition induced by the presence of 300 p.p.m. of zinc in exchangeable form. Jones, Gall and Barnette made a systematic study of the fixing power for zinc of representative Florida soils. Soluble zinc was very readily leached from open-textured sandy soils. Phosphates exerted a positive influence on fixation. The increased fixation of zinc by the addition of colloidal phosphate to a Norfolk sand indicates that those

soils which are formed from phosphatic materials or contain large quantities of these materials are capable of fixing large quantities of zinc in an insoluble form and thus decreasing its solubility in the soil.

Replaceable zinc became toxic at concentrations of from 0.28-2.2 milli-equivalents per 100 gms. of soil (180-1400 lb. per acre) depending on soil and crop.

In soils zinc is present in minute quantities. Analyses show from 2 to 50 p.p.m., the lowest quantities being found in sandy soils. It is known that various soils have different capacities for fixing zinc; clay, organic matter and salts being important factors in the fixation process. In an account of a zinc survey of Californian soils the amount of zinc found was in general from 1 to 5 p.p.m., though certain samples contained more. Zinc accumulated from the vegetation in the surface humus soil and was only slowly leached down because of the high fixing power of the soil for zinc. In alkaline soils, even when the supply was adequate, the zinc appeared to be largely unavailable to plants.

The growing volume of literature on the minor elements in the soil is indicative of the importance attached to the subject by agricultural scientists. Although many new cases of apparent minor-element deficiency have been brought to light within the last ten years, it cannot be said that our knowledge of the actual roles played by sometimes infinitesimal quantities of certain substances in the metabolism of either plant or soil has advanced very far.

The problem of the addition of secondary elements to commercial fertilizers is a complicated one and must be conservatively handled. The compatibility of carriers of secondary elements with other ingredients of the fertilizer mixture is to be considered. It will frequently be difficult to obtain a uniform mixture of the small amounts required. In many cases the chemical reaction of the clay or absorption complex, as well as the question of economy, will be a determining factor. Thus the addition of a pure manganese salt to a clay saturated with calcium will very soon result in the precipitation of insoluble manganese dioxide. A similar reversion to an insoluble form apparently occurs with zinc.

The lack of accurate information on the content of secondary elements in soils and plants and the effect of small quantities of these elements on animal and human health constitutes an important problem for further research.

*The Soluble Matter in Soils and the Soil Solution*

**The Soil Solution.** Water that is held by the soil in the root zone and is available for the use of crop plants is called the soil solution. The nature and concentration of the dissolved substances are matters of the first importance. This is because these dissolved substances are the only source of the mineral elements essential to plant growth, and also because they may include elements injurious to crop plants or the concentration of which in the solution may be such as to hinder the absorption of the water by the plants. Under conditions of copious rainfall and of free root-zone percolation the need may be to maintain in the soil solution adequate concentrations of the constituents that are essential to normal crop growth. With irrigation however, and particularly with restricted root-zone percolation, there is another danger, namely, that excessive concentrations of dissolved constituents may accumulate in the soil solution. It is possible, that the soil solution may be at the same time inadequately supplied with some essential constituents or contain an excess of others.

In irrigation farming it is important to maintain in the root zone of the soil an adequate quantity of water to supply the continuing needs of the crop plants, on the one hand preventing excessive root-zone leaching and on the other, insuring sufficient leaching to prevent the accumulation of excessive concentrations of dissolved salts. In situations where the irrigation water is relatively pure, losses or injuries from excessive leaching may be avoided by restricting the quantities of water applied. But when the irrigation water contains relatively large quantities of dissolved salts it becomes necessary to use it in sufficient quantities to insure root-zone leaching and thus prevent the accumulation of excessive concentrations in the soil solution. It follows, of course, that there must be effective subsoil drainage, either natural or artificial, to permit the removal of the percolating soil solution with its dissolved salts.

**Water Relationships of Soil.** Soil as a material has the capacity for water retention, partly on account of its obvious porosity but still more on account of the presence in it of clay and humus, both of which have an enormous capacity for water retention. Indeed, the differences in water-holding capacity of soils are almost entirely due to their different contents of clay and humus. We should perhaps note that humus has a greater capacity for water retention than has clay. Peaty soils can retain very large quantities of moisture.

The amount of water in the soil depends on its texture. When rain falls, part of the water penetrating the soil is retained and used by plants, any excess water being removed by drainage. In the soil, interstitial spaces occur between the soil particles. These are termed pore spaces into which the water can penetrate. The soil water can be divided into three types.

(a) Free or gravitational.

(b) Capillary.

(c) Hygroscopic.

(For full details about these kinds of soil water refer to books on soil physics.)

The thermal movement of water at the soil surface is very rapid and of great importance in farming operations. The soil moisture is exposed to sun and wind, and evaporation goes on rapidly, the free, capillary, and a part of the hygroscopic water being subject to such loss. Since the free water usually sinks into the soil and the hygroscopic is protected by the capillary, it is the latter that is most affected. Again, the capillary moisture usually makes up most of the water present in soil, and, as it is loosely held, its loss by evaporation is very rapid.

It is interesting to note that H. Lowly has shown that desert soil normally contains no gravitational and no capillary water ; and that its moisture consists exclusively of adsorbed films of water. The surface layers of these films are electrically conducting if the film thickness is not too small. With diminishing thickness, however, a stage is reached where the whole film consists of solidified water.

(1) **Maximum Water Capacity.** This is the maximum amount of water held in the pore spaces, and it varies with the size distribution of the particles. It is determined directly by means of a brass cylinder, with a perforated base, fitted with a brass base cover. It is filled with soil and immersed in water to its upper edge, so that water percolates upwards and fills the pore spaces. The cover is then

replaced, and the cylinder re-weighed. This maximum capacity is the basis for calculating other water figures.

(2) **Maximum Retentive Capacity.** This is the amount of water held by the soil against gravity, and is determined by allowing the water to drain off from the soil in the previous experiment and preventing evaporation during the process.

(3) **Hygroscopic Water.** This is the amount of water held by the soil in the air-dry condition, and which is driven off by heating in an oven. The oven-dried soil on exposure to moisture will also take up a definite amount of water. Measurement of the hygroscopic water can be used for ascertaining the proportion of colloidal matter in the soil by keeping a weighed amount in a chamber of a definite percentage humidity maintained by a 3-4 per cent.  $H_2SO_4$ , until constant in weight.

**The Composition of the Soil Solution.** As has often happened in the history of agricultural science, the first investigation on this subject was made in France ; Schloesing, in 1866, devised a method of separating the soil solution from the soil mass based on displacement by water. He placed 30 to 35 kg. of fresh field soil in a large inverted tubulated bell jar and poured on it water, coloured with carmine, in such a way as to simulate the action of rain. The added water at once displaced the soil water and caused it to descend so that it could be collected : a sharp horizontal line of demarcation between the added and the original water persisted throughout the experiment even when eight days were occupied in the descent. A typical analysis of the displaced liquid in milligrams per litre was :—

	Nitric Acid	Carbonic Acid	CaO	MgO	K <sub>2</sub> O	Na <sub>2</sub> O	Sulphuric Acid	Chlorine	Organic Matter	
SiO <sub>2</sub>	29.1	305	118	264	13.5	6.9	7.8	57.9	7.4	37.5

and in addition traces of phosphorus and of ammonia. This soil contained 19.1 per cent. of water.

Soil solution can be obtained undiluted by :—

(a) *Application of heavy pressure.*

Morgan expressed the soil solution from moist soil by using steel cylinders and plungers. He obtained soil solutions the composition of which differed from that of water extracts obtained by filtering a suspension of soil in a large excess of water.

(b) *Displacement Methods.*

Parker packed long columns of moist soil in tubes and displaced the soil solution with alcohol as this does not cause dilution. He

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found that the composition of this displaced solution agreed with that obtained by pressure methods. Successive portions of displaced soil solutions showed constant composition until alcohol appeared.

Temperature affects the composition of the soil solution by influencing bacterial activity, and possibly to some extent through its influence on the solubility of soil constituents. If the soil is frozen, abrupt changes in the composition of the soil solution occur ; also, repeated freezing and thawing may accentuate these changes, hence sampling is to be avoided after a hard frost. Bouyoucos suggested that repeated freezing liberated some of the "bound" water from soil colloids. In some cases however, prolonged freezing caused considerable change. If soil solution is examined in the field in successive 1" layers, differences in composition from layer to layer are found. To obtain a mean value, a 9" sample is taken, and thoroughly mixed before packing in the tube.

Samples must be firmly packed in order to ensure slow displacement. They must also be fresh since microbiological and other changes occur in stored moist soils.

The soil solution is a solution of mineral and organic salts in equilibrium with the soil, and its composition and concentration varies as the total water content of the soil changes and new equilibria are set up between solid and liquid phases.

**Mineral Ingredients of Soil Solutions.** It is essential to an understanding of the plant, the interactions between soil and the composition of soil solution, to keep in mind that it is the salt ions rather than actual molecular salts which are important.

The soil-solution constituents ordinarily identified by analysis are the following :—

- (1) Calcium (Ca).
- (2) Magnesium (Mg).
- (3) Sodium (Na).
- (4) Potassium (K).
- (5) Iron (Fe).
- (6) Aluminium (Al).
- (7) Manganese (Mn).
- (8) Carbonate and bicarbonate ( $\text{CO}_3$  and  $\text{HCO}_3$ ).
- (9) Sulphate ( $\text{SO}_4$ ).
- (10) Chloride (Cl).
- (11) Phosphate ( $\text{PO}_4$ ).

In some situations small proportions of boron and selenium and other

elements occur in the soil solution. Certain physical characteristics of the solution are also of significance, e.g., the specific electrical conductance, and the hydrogen-ion concentrations.

The concentration of nitrate varies inversely with the moisture content, indicating that the whole of the nitrate in the soil is dissolved in the soil solution.

The concentration of phosphate, though varying from soil to soil, is largely independent of the moisture content, the soil solution being presumably saturated with phosphate and dissolving more or throwing some out of solution according to the variations in water content ; usually about 1 to 3 parts per million are present.

The concentration of potassium increases as the soil solution becomes more concentrated, but not proportionally. This suggests that the available potassium is not all dissolved in the soil solution at the outset, but that it is partly in the solution and partly absorbed by the soil : the solution and the soil are in some kind of equilibrium. This applies in varying degrees to all other bases in the soil solution.

The total concentration of the soil solution in ordinary agricultural soils, and excluding saline soils, is usually about 0.05 to 0.02 per cent. ; the osmotic pressure is about 0.2 to 1 atmosphere. The variations in the composition of soil solution are relatively much smaller than those in the root sap of plants growing in the soil, the osmotic pressure of which is some 7 to 20 atmospheres. It is not at all clear how the ions pass from the soil into the root.

**Organic Contents of Soil Solution.** Some soil solutions are colourless, but may contain considerable organic matter, representing the end-products of biological oxidation by micro-organisms. The coloured organic matter is associated with the humus, and its solubility depends on the pH, being less at high levels of acidity. Thus excessive liming of a soil will tend to remove more organic matter by drainage as a result of its greater solubility. The concentration of mineral salts also controls the colloidal dispersion of coloured organic matter ; the less the concentration the greater the dispersion.

Phosphorus in the soil solution occurs, partly, in organic forms, e.g., nucleic acids. Since ordinary crop plants use mineral phosphorus, there must be a phosphorus cycle in which bacterial action occurs. The bacterial action is shown by adding farm yard manure when increase in the inorganic phosphorus occurs in the soil solution. If green manure is used, considerable difference is seen.

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This difference is due to the fact that with farmyard manure a large bacterial population is added to the soil.

The chemical composition of the soil solution varies greatly according to the character of the soil, climatic conditions, fertilization, methods of culture, and other environmental influences. While actual analyses of soil solutions from different regions are few, the differences in composition are partially indicated by the composition of the river water of different areas.

Table 13 shows the average composition of soil solutions analysed by the author at the laboratories of the Imperial College of Science (University of London).

TABLE 13  
*Average composition of soil solution.*

No.	Constituents	p.p.m. (Parts per million of oven dry soil)
1	Calcium ... ..	500
2	Magnesium ... ..	50
3	Potassium ... ..	40
4	Sodium ... ..	90
5	Manganese ... ..	10
6	Aluminium ... ..	6
7	Iron ... ..	3
8	Phosphate ... ..	2
9	Sulphate ... ..	200
10	Chloride ... ..	800
11	Ammoniacal Nitrogen ... ..	4
12	Nitrate Nitrogen ... ..	60
13	Organic Nitrogen ... ..	50

**The Effects of Continuous Cropping and of Fallowing upon the Composition of the Soil Solution.** The effects of continuous cropping and of fallowing upon the composition of the soil solution have been studied especially by Burd and Martin, who divided samples of each of seven well-mixed soils into three portions. On one portion of each barley was grown for 8 years ; a second portion was cropped the first year, but kept fallow the remaining 7 years ; a third portion (original unplanted soil) was kept in a closed bin during the 8-years period. Soil solutions, obtained by water displacement from each of these portions of the seven soils were analysed. The average analyses are given in Table 14.

TABLE 14

*Average composition of soil solutions from cropped, fallowed, and air-dry stored soils after 8 years.*

Ingredient	Displaced solution from		
	Cropped soil p.p.m.	Fallowed soil p.p.m.	Stored soil p.p.m.
Carbonic Acid ...	85	53	73
Sulphuric Acid ...	472	394	238
Nitric Acid ...	181	1,560	1,043
Phosphoric Acid ...	1·8	1·7	5·3
Chlorine ...	—	43	263
Calcium ...	203	559	381
Magnesium ...	86	134	107
Sodium ...	42	64	116
Potassium ...	27	63	75
Silica ...	—	—	48
Total solids ...	1,097	2,871·7	2,349·3
Per cent. ...	0·11	0·29	0·23

The solution from the fallowed soil, as compared with that from the original stored soil, shows an increase in sulphate, nitrate, calcium, magnesium, and total solids, but a decrease in carbonic acid, phosphoric acid, chlorine, sodium, and potassium. The solution from the cropped soil, on the other hand, shows a great decrease in all constituents except carbonate and sulphate. These decreases give a good indication of the great losses in mineral nutrients sustained by soils as a result of cropping and leaching.

**Soil Solutions and Water Extracts.** At the dilutions ordinarily encountered in the soil solution, the salts are almost entirely dissociated into their component ions. In considering the equilibria between the solid phase of the soil and the soil solution, it is therefore necessary to think in terms of ions rather than salts. Thus, the soil solution has a certain concentration of calcium-ion and this concentration will vary with the ratio of soil to water.

If  $y$  be the concentration of calcium in the soil phase, and  $C$  the concentration in the soil solution phase, it is found that  $y = K.C^{1/p}$ ,  $K$  and  $p$  being constants. This is the well known Freundlich equation, which applies to the adsorption of substances from solutions by colloids. The equilibria of most ions are governed by the same law, although with different constants. The fact that experimental results fit the Freundlich equation must not, however, be taken as

proving that these equilibria are due to colloidal adsorptions analogous to the bodily adsorption of dyes by charcoal, for the equation will serve equally well for many non-colloidal heterogenous equilibria.

Certain ions do not obey the Freundlich equation, notably chloride and nitrate, these ions are not ordinarily adsorbed by soils and there is, thus, no "soil-chloride", or "soil-nitrate" with which they are in equilibrium. The concentration of these ions in the soil solution, in the absence of any removal by leaching or root absorption, will therefore be inversely affected by the ratio of water to soil.

The above considerations should make it clear why the soil solution cannot be investigated simply by adding a known volume of water to a given weight of soil, filtering, and analysing an aliquot of the filtrate for the purpose of calculating back to the original water content of the soil.

**The Freezing Point of the Soil Solution.** It is well known that the freezing point of water is lowered by the presence of salts in solution. The basal law involved states that the depression of the freezing point is proportional to the concentration of the solution. If, therefore, a solution has a freezing point of  $-\Delta$  °C., it will, after 50 per cent. of the water has evaporated and the solution therefore become twice as concentrated, have a freezing point of  $-2\Delta$  °C. If the original  $V$  c.c. be reduced by evaporation of the water to  $v$  c.c. the freezing point should be

$$-\frac{V}{v}\Delta \text{ }^{\circ}\text{C.}$$

The depression of the freezing point of the water in moist quartz sand and in various types of soil has been examined by Bouyoucos. A few figures illustrating his results are given in (Table 15). It will be

TABLE 15

	Quartz Sand			Sandy Loam			Clay Soil		
Per cent. Moisture ...	18	10	2	21	15	7	34	24	18
Depression of f.p. (°C.) ... ..	.009	.018	.091	.023	.065	.390	.034	.212	.922
Depression of f.p. calculated from that at highest water content ... ..	—	.016	.081	—	.035	.075	—	.048	.064

seen that the solution permeating quartz sand obeys the law relating concentration to depression of the freezing point reasonably well, but the soil solution in contact with the soil appears not to do so. When water evaporates from the soil, the depression of the freezing point increases far more rapidly than the law indicates. Evidently the soil solution becomes far more concentrated on evaporation than would be expected. This is likely to happen if some part, and not the whole, of the water behaves as an ordinary solvent.

**The Nutrient Elements as Solutes.** It has already been emphasized that soil solutions may exist in a state of minute subdivision. Moreover, it is differentially adsorbed by the colloidal surfaces, part being held tightly and having little movement, while some suffers but slight restraint and circulates more or less freely. Again the soil solution is exceedingly changeable, varying as to the gross amount present in any soil, as to total concentration of dissolved salts as well as to the amount and proportion of specific constituents. It now remains to follow the nutrient elements, especially those of a primary nature, into this surprisingly dynamic biological medium.

When the solution is dilute a considerable proportion of the soluble constituents are present as ions. As the solution becomes more concentrated, during a dry spell for example, the proportion of the soluble substances in molecular association tends to increase. This same condition, but much accentuated, holds true for arid region soils also.

Certain explanations should be made regarding the use by plants of the ions carrying nitrogen, phosphorus, and sulphur. Most of the nitrogen apparently is absorbed in ammoniacal and nitrate forms, depending on the condition of the soil, the kind of plant, and its stage of growth. In general the presence of both ions seems most favourable for the growth of the plant. When nitrification is active, nitrites are oxidised so readily to the nitrate form that little can accumulate.

In arid and semi-arid regions the soil solution is usually much more concentrated than where the rainfall is heavier, so much so as to interfere at times with the growth of plants. The presence of even 0.5 per cent. of total soluble salts is considered serious. This would mean 10,000 pounds to the acre-furrow-slice.

The type of phosphate ion present in soil solutions is determined by the pH of the soil. When the soil is distinctly alkaline the

$\text{PO}_4'''$  ion apparently predominates in the soil solution. This form is utilized least readily by crops. As the pH is lowered and the soil becomes slightly to moderately acid, the  $\text{HPO}_4''$  and  $\text{H}_2\text{PO}_4'$  ions increase, while at high acidities the phosphorus is present largely as  $\text{H}_2\text{PO}_4'$ . These two forms, especially the latter, are readily absorbed by higher plants. This influence of pH on the availability of phosphorus is thus pronounced and has a very important bearing.

In the case of alkaline soils, Shawarbi has shown that the disappearance of phosphates from soil solutions obtained from such soils is not due to their pH or alkalinity, i.e. to the predominance of the mono-valent bases in the soil colloidal complex, but is due to the presence of free electrolytes with which these soils are usually impregnated.

The pH also has an important influence on the availability of manganese, iron, and perhaps other nutrients. In fact, the respective preponderance of H or OH ions seems to be associated with soil conditions that profoundly affect micro-organisms and higher plants. In addition they function as sources of hydrogen and oxygen. A list of nutrients is thus incomplete without them.

The presence of  $\text{Fe}^{+++}$ ,  $\text{Al}^{+++}$  and  $\text{Mn}^{++}$  is typical of acid conditions, increasing in summer and decreasing in winter, due to marked biological activity in the warmer months, and to production of  $\text{CO}_2$ . Mn, however, rarely appears in soils of pH 7. At pH 6.7-6.8, Mn appears in the soil solution, increasing as pH decreases. Liming causes Mn to disappear. At the neutral point, stable Mn silicates are formed and thus the neutral point represents the point of minimum solubility. Aluminium appears at pH 4.4-4.5 but very little Fe, until pH 3.6-3.7 when large amounts of Fe appear. Thus Mn, Fe and Al appear in zones of pH which are in close agreement to the pH zones at which decomposition of metallic silicates begins. These metals are thus probably present as complex silicates. Exceptions occur in organic soils where Al and Fe form complexes which may give Fe and Al in solution at pH values other than those which apply to silicates.

The carbon dioxide of the atmosphere is the direct source of most of the carbon required by higher plants. In the soil solution carbonates and bicarbonates occur in abundance, which, when dissociation occurs, develop  $\text{CO}_3$  and  $\text{HCO}_3$  ions. If these are absorbed by higher plants, and there seems no reason why they should not be, carbon might thus be acquired. In fact, at times a considerable amount of carbon probably enters the plant directly from the soil.

✓ **The Intake of Soil Constituents by Plants.** A proper understanding of availability is clearly dependent upon a true conception of the mechanism whereby plant food in the soil enters the plant. This crucial problem is still a little obscure. There appear to be three possibilities which may be briefly discussed :—

- (1) Solutes already in true solution in the soil water diffuse into the root hair cells.
- (2) The plant brings soil constituents into solution by some means or other.
- (3) Colloids as well as true solutes enter the root hairs.

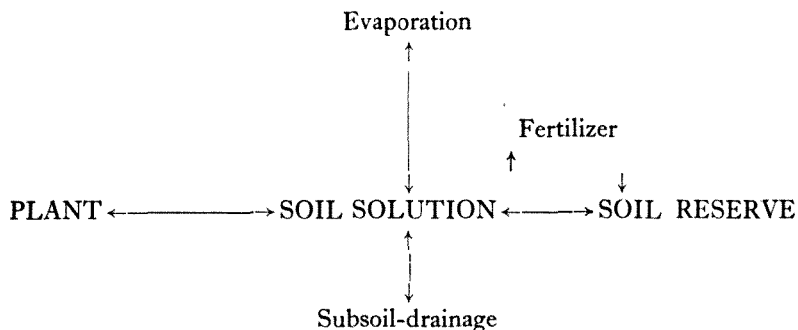
Among botanists and soil chemists the usual and "orthodox" views have until recently involved only the first of these possibilities. The others are not altogether denied as possibilities, but it is held that the first is the most obvious and natural assumption, and is adequate to explain the facts. The plant growing in soil is regarded as being in much the same position as the plant growing in a culture solution, except that in the soil the solution is spread over a lot of particles instead of being contained in a bottle. Whether that is the whole story or not, it is clear that absorption from solution must play a prominent part in plant nutrition. Nitrate, for example, occurs entirely in solution in the soil under ordinary conditions.

Although plant physiologists have abandoned the old view that root cells excrete their contents into the soil, it is still possible for the root hairs to "attack" the soil particles. As the root hairs grow among soil particles they develop a mucilaginous colloidal surface which merges with the colloids of the soil crumb so that the soil and the plant become irrevocably attached, forming one system. The soil particles can never be detached from the root hairs without tearing them. The root hairs do not just dip into the soil solution : they are united with the particles. It is therefore possible for the organic colloids and solutes of the root hairs to withdraw mineral constituents from the soil. The uptake of iron, etc., by plants from alkaline soils and by lichens, etc., from limestones may be a consequence of this type of action. Mineral phosphates appear to have colloidal properties not unlike those of soils, and their service to the plant may very well be due in part to the union between them and the root hairs. The effect of basic slag on wild white clover, for example may be due, not so much to the dissolution of the phosphate and its dissemination throughout the soil solutions, as to the presence among

the soil particles of additional phosphatic colloidal particles with which the root hairs make their union and which they attack.

**Harmful Substances Taken up from the Soil.** It used to be thought that anything taken up by the plant must be for the good of the plant, and, arguing from this assumption, the analysis of the plant was taken as a guide to its manurial requirements. It is now known that this idea is wrong ; the plant may take up some of whatever substance is in solution in the soil water, regardless of whether its effects will be good, bad or indifferent. The plant is, however, not quite as helpless as a sponge ; it has a certain, but not very great, selective power.

**The Soil Solution and Soil Fertility.** The fertility of the soil is its ability to maintain a satisfactory supply of nutrients to growing crops, and hence the soil solution is an index of this fertility at any particular moment. There is also an equilibrium between plant, soil solution and soil reserve, thus :—



The soil solution contains the whole of the nitrate that is ready for the plant, some of the potassium, but only a fraction of the phosphate. It contains as we have seen some 50 to 300 parts per million of nitrate nitrogen, 10 to 40 parts of potassium, but only 1 or 2 parts of phosphate ( $\text{PO}_4$ ). Broadly speaking the more fertile soils have the more highly concentrated soil solution, but there is no close connection between fertility and concentration, indeed, in water-culture experiments dilute solutions may give as good growth as concentrated solutions, provided they are renewed sufficiently rapidly.

**The Biotic Conditions in the Soil.** The rate of renewal of the dissolved substances is one of the important properties of the soil-water system. For phosphorus it must be considerable, for potassium the question of renewal is usually less important since more of it is

present in the soil solution but for nitrate the rate of renewal is dependent entirely on the activity of the micro-organisms.

**Water Supply and Soil Fertility.** For every part by weight of dry matter formed, from two hundred to one thousand parts by weight of water must be absorbed by the roots of plants. Of all the factors affecting plant growth, water-supply probably has the greatest weight in deciding the differences in crop-producing ability between one soil and another.

Water supply, however, has proved very difficult to study quantitatively because the need for water is continuous, but the amount required varies greatly with the conditions and according to the stage of growth of the plant. The close relationship between water supply and effectiveness of nutrients was clearly established by C. Von Seelhorst at Gottingen in pot experiments. Increases in nutrient supply has little effect in the rather dry soil, but an increasing effect as the water supply rose up to a certain point. Also, the effect of the water increased as the nutrient supply was raised.

This marked interaction of water and nutrient effects is well brought out in the field experiments on cotton carried out in the Gezira by F. G. Gregory and F. Crowther and A. R. Lambert—perhaps the best field experiments yet made on the subject. Only the first series need be quoted; the second was complicated by varying the spacing and sowing date but it gave similar results. Water was supplied at three rates, and sulphate of ammonia at two: the yields of seed cotton were, in kentars per feddan:—

TABLE 16  
*Influence of Water and Nitrogen Supply on the Yield of Seed Cotton.*

Nitrogen Supply	Rate of Watering		
	Light	Medium	Heavy
No added Nitrogen ... ..	1·38	1·54	1·58
300 Kg. Sulphate of Ammonia ... ..	1·98	2·45	2·80
600 Kg. Sulphate of Ammonia ... ..	2·28	3·04	3·70

Additional water was almost ineffective in absence of added nitrogen, but greatly increased the yield when nitrogen was given, and it enhanced the effect of each level of nitrogen supply. ✓

#### THE CONTROL OF WATER IN THE SOIL

**Irrigation.** In sections where the average rainfall is of sufficient

amount and well distributed throughout the growing season, it is possible to produce good yields of crops on most soils. In the drier areas where the average annual rainfall is less than 20 inches, the practice of irrigation, or the application of additional water, is much more common. In the semiarid and arid regions, the rainfall, including the snow, is usually concentrated during the winter months, and very little during the summer. Therefore, it is essential to practise irrigation in these areas in order to ensure good crop growth and to produce a greater variety of crops.

**Management of Irrigated Soils.** The essential features in the management of irrigated land are :—

- (1) The exclusion of soluble salts.
- (2) The removal of excess of water from the soil and the keeping down of the level of the subsoil water.

**Salt and Water Problems.** Sodium salts may be brought into irrigated land in two ways :—

- (1) In the water used for irrigation.
- (2) By seepage from higher land.

The likelihood of injury depends on the texture of the soil and on the drainage : a light sandy well-drained soil is most tolerant of salt, and a heavy badly-drained soil is the least tolerant.

Irrigation may also raise the ground-water level, and since the ground water in general contains large quantities of salts its ascent may spoil a great deal of land and, in any case, it may asphyxiate the roots. For a full account of the development of saline and alkaline soils see Chapter 13.

**Drainage.** While percolation, especially in humid regions, causes the loss of a large proportion of the rainfall received and carries away in addition many tons of soluble material, it is generally wise to facilitate it, at the same time checking as much as possible by means of crops the loss of available nutrients. The encouragement of percolation is spoken of as "land drainage," which is the process of removing the excess or superfluous water from the soil as rapidly as possible. Practical farm drainage is paramount in almost every community, even in arid regions where irrigation is practised.

**The Benefits derived from Artificial Drainage.** As would be expected, the improvement in soil conditions produced by drainage is reflected in a material increase in crop yields. The main benefits derived from artificial drainage are :—

- (1) *Increase in water available to crops.*—The removal of excess

water by drainage actually increases the quantity of water available to plants. At first thought, this statement may appear paradoxical. Plants on the drained soil have several times the depth of root zone and consequently several times the total reservoir upon which to draw for the capillary water needed for growth.

(2) *Aid to bacterial action.*—Many of the organisms that aid in producing conditions in the soil that are favourable for crop plants do their work only in the presence of atmospheric oxygen. Since oxygen is largely excluded from waterlogged soils, it is obvious that these helpful organisms cannot function in such soils until the soils have been drained and aerated. Moreover, certain organisms live and work in the water. Not only does this group break up plant nutrients that had been prepared by the helpful group, but the harmful ones may produce substances that are toxic or poisonous to crops. Here, then, is a further reason for the removal of excess water from the soils on which economic plants are being grown.

CHAPTER II

*The Gas Phase of the Soil*

THE first important attempt to analyse the soil air was made in France about ninety-five years ago. Later, and with the help of new methods, a number of analyses were made, and in 1915 the results of an important and systematic investigation of the subject carried out at Rothamsted by Russell and Appleyard were published.

The recent investigations in America, England and Germany all consistently indicate that the composition of the soil air is not vastly different from that of ordinary air. The following figures show the approximate composition of dry soil air and dry atmospheric air. The figures are percentages by volume.

TABLE 17

Constituents	Soil air	Atmospheric air
Oxygen ... ..	20·6	20·99
Nitrogen, etc. ... ..	79·2	78·95
Carbon dioxide ... ..	0·2	0·03

The difference between the average composition of dry soil air and that of dry atmospheric air is not great. There are, however, three things to be mentioned.

1. The soil air contains seven or eight times as much carbon dioxide as atmospheric air.
2. The variation in the composition of soil air is considerable when compared with the variation in the composition of atmospheric air.
3. The soil air is generally saturated or nearly saturated with water vapour.

Like the soil solution, the soil air is a dependent phase and its composition varies even in the same soil. In arable soils the percent-

age, by volume, of oxygen usually exceeds 20.3, that of nitrogen is usually about 79, while the carbon dioxide varies from about 0.15 to 0.65. The chief variable, the CO<sub>2</sub>, increases with the amount of organic matter in the soil and with temperature and moisture content ; it is higher in summer than in winter. It increases also when the crop is growing. H. W. Turpin found in pot experiments 0.3 to 0.95 per cent. of CO<sub>2</sub> in the air of uncropped soils, but 0.3 to 2.0 per cent. in the air of cropped soils. In soils covered with grass, notwithstanding the greater pore space, the air contains more CO<sub>2</sub> and appreciably less oxygen, usually 18.2 per cent., but sometimes less than 17 per cent. (See Table 18).

TABLE 18

Type of soil	Oxygen per cent. by volume	Nitrogen per cent. by volume	Carbon dioxide per cent. by volume
Soil air (arable)	20.5	79.2	0.3
Soil air (pasture)	18.2	80.2	1.6

This increased CO<sub>2</sub> production on cropped land may contribute to the nutrition of plants by increasing the concentration of CO<sub>2</sub> in the lower layer of air in which the leaves are functioning.

The presence of more carbon dioxide in the soil air than in the atmosphere is readily demonstrated by driving a  $\frac{1}{2}$  in. gas pipe to a depth of 6 in. in the soil and connecting it with a test-tube containing 20 c.c. of baryta water and attached to an aspirator. A similar tube also containing 20 c.c. of baryta water but open to the air is attached to the same aspirator. Set the aspirator working and arrange the connections so that bubbles pass at the same rate through the two lots of baryta water. The one connected with the soil speedily becomes turbid, indicating the presence of carbon dioxide ; the other, open to the air, however, only shows turbidity later on.

**The Cause of the Relatively High Carbon Dioxide Content of Soil Air.** The main cause of the comparatively large percentage of carbon dioxide in soil air is the activity of micro-organisms. This is indicated in two ways.

(1) Firstly, the treatment of the soil with antiseptics prohibits the further production of carbon dioxide.

(2) Secondly, the fluctuations in the amount of carbon dioxide are roughly parallel to the fluctuations in the amounts of other products which are known to be the result of micro-organic activity.

Russell and Appleyard studied in detail the causes of fluctuations in the composition of the soil air under English conditions and came to the conclusion that these variations were chiefly due to fluctuations in the rate of biochemical changes. From November to May, temperature seemed to be the determining factor in  $\text{CO}_2$  production. From May to November,  $\text{CO}_2$  production followed the rainfall; soil moisture was the limiting factor during the warmer months. A maximum in the  $\text{CO}_2$  content of the soil air was observed in the late spring and a minimum was found in summer and winter.

Several American workers have studied independently the relations between the production of carbon dioxide and the production of ammonia. At Rothamsted, Russell and Appleyard studied the relation between the production of carbon dioxide and the production of nitrate and also that between the production of both carbon dioxide and of nitrate and the bacterial numbers. There is a rough parallelism between the carbon dioxide produced, the nitrate produced, and the bacterial numbers. The curves are not absolutely parallel but they are sufficiently similar to justify the conclusion that all these things are related. Furthermore, that conclusion is consistently supported by the results obtained in America.

So far we have been dealing with conditions in temperate and humid climates only. Leather's determinations at Pusa suggest that the  $\text{CO}_2$  in the soil air may be much higher, some of his values varying from 1 to 5 per cent., while the oxygen fell considerably; during the hot, dry season of April and May it was sometimes only 16 to 18 per cent., and during the rains (monsoon) of June and July it fell to 8 to 12 per cent. Others of his values, however, are not unlike those of temperate climates.

The carbon dioxide in the soil atmosphere is not all that is present in the soil. Some is dissolved in the soil water. Its exact amount depends on the other dissolved substances and the way in which the equilibrium with the soil air is affected by the presence of the soil colloids. Leather's calculations suggested large amounts of dissolved  $\text{CO}_2$  but direct determinations would be desirable.

The nitrogen in the soil air is the source from which the nodule organisms derive their supplies. A crop of lucerne fixes about 1 cwt. of nitrogen per acre in three months.

**Soil Air and Radium Emanations.** The soil air contains radium emanations of the order of  $103 \times 10^{-12}$  curies per litre at a depth of 50 cms., this being many thousand times greater than the

amount found in atmospheric air ; these have been studied in detail by L. B. Smith.

Many experiments have been made to discover whether the rays or emanations have any effect on the growth of plants or micro-organisms. Some degree of stimulation of various processes has been claimed from time to time, but no clearly proved increase in plant growth has yet been obtained. So far as present evidence goes, the "Radioactivity" periodically offered to farmers as a fertilizer is worthless.

**The Dynamic Nature of Soil Air.** As a result of its peculiar associations, the soil air is markedly heterogeneous as to position, movement and composition. Some is absorbed by the colloidal surfaces and thus is in close contact with the soil solids. Such air is very high in carbon dioxide and has slow if any movement at all. Some occupies the larger interstices, is free to move from place to place, and contains large quantities of oxygen and a minimum of carbon dioxide. Besides this heterogeneity, the atmosphere of the soil is dynamic, changing constantly in amount and composition. A fluctuation in the soil-water automatically varies the amount of air present, while any condition that increases or decreases carbon dioxide production must certainly modify the proportion of the various gases present.

The soil air, because of its varying amounts of carbon dioxide and oxygen, presents to the roots of higher plants and to micro-organisms an atmosphere suited to almost any type of biochemical activity. Aerobic and anaerobic organisms flourish side by side while reduction, oxidation, and synthesis may occur simultaneously in the same soil. The dynamic nature of such an atmosphere is such as to force rapid adjustment upon any plant or animal that attempts to function within it. This is a phase that must be reckoned with in biological studies of natural soils.

**Air Supply.** The soil being a porous mass, air can enter and pass out both by direct streaming and by diffusion. The amount that enters and the rate of entry depend on the pore spaces which in turn are determined by the size, shape, and mode of arrangement of the soil particles. But the pore space has also to hold the soil water, so that a knowledge of its amount gives only the maximum space available for air.

The space occupied by air at any time is calculated by deducting the volume of the water present from the total pore space, it being

assumed that the volume of moist soil is the sum of the volumes of the solid particles and the water, an assumption, which, while not strictly true, is probably not far wrong.

W. Mathy has shown that air permeability of soil depends on pore volume and on the air and water contents. Three kinds of pores are distinguished : (1) large pores not holding water but transmitting air ; (2) macrocapillary pores, holding water and transmitting air ; (3) microcapillary pores holding water intensely and scarcely permeable to air. Ploughsoles and pans contain mainly the last kind of pores, and their presence has a harmful effect, which can be remedied by breaking them up, on the movement of air and water through the entire soil.

Most of the present data on the composition of the soil air indicate that the amounts of  $\text{CO}_2$  and  $\text{O}_2$  do not vary much within the immediate surface. There may be some question as to the applicability of these data to all soil conditions, especially to rather impervious soils. Nevertheless, in light of the intensity of  $\text{CO}_2$  production through plant growth and microbiological activities, the apparent lack of any large accumulation of  $\text{CO}_2$  in the surface soil (often true of the sub-soil) suggests a rather rapid exchange of gases with the atmosphere. The renewal of the soil air is brought about by diffusion and the meteorological factors : soil temperature changes, barometer variations, action of the wind and changes in the amount of pore space occupied by air as a result of the entrance of rain or irrigation water.

**Diffusion.** Buckingham was one of the first investigators to apply the kinetic theory of the diffusion of gases to soil aeration. Since, according to the kinetic theory of gases, the molecules of gases are in a state of movement in all directions, two gases will readily mix as the molecules of each gas move into the space occupied by the other. This process is usually known as diffusion. Inasmuch as the soil air tends to contain more  $\text{CO}_2$  and less  $\text{O}_2$  than the atmosphere, the diffusion process in soils consists primarily in the movement of  $\text{CO}_2$  out of the soil into the atmosphere and of  $\text{O}_2$  from the atmosphere into the soil. If this action is complete until equilibrium is attained, there will be a tendency for the soil air to approach the composition of the atmosphere.

Buckingham applied the term diffusion constant to designate the rate of flow of gases through the soil-pore space as a result of kinetic movements. This constant was defined as the average number of

cubic centimeters of each of two gases which would pass in opposite directions through a layer of soil one centimeter thick, per second, per square centimeter of cross section, when the partial pressure of each gas was one millimeter of mercury greater on its respective side of the layer than on the other. Each gas diffuses through the soil layer to the side where its partial pressure is lower.

He also found a definite correlation between the free pore space (total pore space not filled with water) and the diffusion constant. The addition of water to the soil layer caused large decreases in the rate of diffusion. These results confirm the findings of Hannen, who showed that the sum of the cross-sectional area of the effective pore volume was the most important factor affecting the diffusion of  $\text{CO}_2$ . On the basis of these data, Buckingham expressed the relation of the diffusion rate to the free pore space by the equation :

$$D = kS^2$$

where  $D$  is the diffusion constant,  $S$  is the free pore space and  $k$  is a proportionality factor or diffusion coefficient, which was calculated to be  $2.16 \times 10^{-4}$ . The value of the diffusion varies directly with the square of the absolute temperature and inversely with the total pressure. This expression points out that the rate of diffusion is reduced to one-fourth as the free pore space is reduced to one-half.

Diffusion is now regarded as being in all probability the chief factor in bringing about the exchange of soil air. The diameters of the soil pores are small, but, as H. T. Brown and F. Escombe have shown, the rate of diffusion through small pores is not proportionately less than through larger ones ; it is governed rather by the total cross-sectional area of the pore space than by the size of the individual pores.

In spite of the rapidity of diffusion there appears to be local variations in the composition of the soil atmosphere. Leather obtained evidence that the amount of  $\text{CO}_2$  is higher near plant roots than farther away. Localised activities of soil micro-organisms are probably accompanied by variations in  $\text{CO}_2$  output, which, however, are difficult to demonstrate as the taking of even a small sample of soil air means extensive evacuation of the pores.

Penman has determined experimentally the relation between the porosity of a soil and the rate of diffusion of gases and vapours through it. He confirmed that the relation was not dependent on the gas used—carbon disulphide, acetone, carbon dioxide and probably also water giving the same curve—nor on the soil's moisture content.

**The Absorbed Air of the Soil.** Russell and Appleyard found that after evacuating a flask containing soil, their manometer continued to fall, indicating that in addition to the "free" atmosphere of the soil there is an "absorbed" atmosphere which is slowly given up to a vacuum. Their investigations of this atmosphere showed that it contained only insignificant amounts of oxygen. The first portions that were extracted contained carbon dioxide and nitrogen in variable amounts; subsequent extractions withdrew almost pure carbon dioxide.

**Air Supply and Soil Fertility.** It is well known among farmers and gardeners that soil aeration is essential to fertility, but exact measurements are difficult to obtain. The phenomena are more complex than appears at first sight, involving two wholly distinct factors :—

1. The necessity of supply of oxygen to the plant root.
2. The toxic effect of the carbon dioxide which invariably accumulates in a non-aerated soil or other medium.

Plants vary considerably in their sensitiveness to these factors. The investigations of Cannon indicate two "cardinal concentrations" of oxygen in the soil air : a lower one beyond which the roots cease to grow, and an upper one at which growth is normal and beyond which further additions of oxygen have no effect : indeed, much more oxygen may do harm. The concentrations differ with different plants ; some, such as rice and certain of the *Salix* family, can continue root growth when the percentage of oxygen is as low as 0.5, others such as maize and peas, need much more. Indeed, for full growth, the 20.97 per cent. of ordinary air is not enough. Even for the same plant the values are not constant but vary with the temperature, being lower at low temperatures than at higher ones, apparently because water has greater power of dissolving oxygen at lower temperatures. The values also depend on the diluting gas, being considerably lowered by the substitution of helium for nitrogen, oxygen diffusing so much more rapidly through helium.

J. B. Whitney has studied the effects of four gas mixtures, of which two contained 20 per cent. of  $\text{CO}_2$  and two had no oxygen, on cotton, maize, tomato, tobacco, sunflower and coleus growing in sand, the gas treatments being continued for 7-14 days. Oxygen lack with or without added  $\text{CO}_2$  resulted in decreased transpiration, and led to death of tomato, tobacco, and coleus roots, and to diminished root-hair development of the other plants.

The growing plant is much affected by carbon dioxide in the soil air in excess of the normal amounts. Stoklasa and Ernest and Lundegardh found that 1 per cent. of CO<sub>2</sub> in the soil atmosphere 15 cms. below the surface retarded growth and was sometimes very harmful. This is in contradistinction to the leaves which may benefit by increasing CO<sub>2</sub> concentration of the atmosphere up to a certain point.

Lawrence Balls has adduced evidence to show that the growth of the cotton plant in Egypt is stopped and the roots killed when the water rises in the soil : as the water falls, however, young roots are sent out again as a result of improved aeration. A. and G. L. C. Howard in India have shown that deficient soil aeration leads to the serious indigo wilt. Improved aeration eliminated the disease and increased the yield. Some of their results with other crops are given in Table 19.

TABLE 19  
*Effect of Improving Drainage on Improving Yield of Crops,  
A. and G. L. C. Howard, India.*

Drainage of Plots	Yield of Cotton, lb. per acre	Wheat lb. per acre
Very bad ... ..	145	370
Fair to Good... ..	366	600
Very Good ... ..	510	1,005

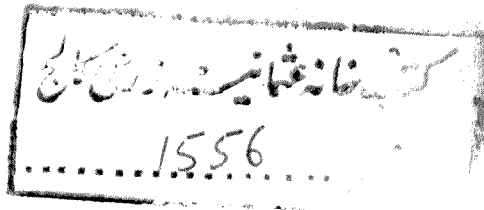
The effect of aeration on plant growth can be seen in (Fig. 12).

**Evolution of Carbon Dioxide and Soil Fertility.** It has been suggested that the rate of evolution of carbon dioxide from the soil is a measure of biological activity and hence of fertility. Whilst this may be true in comparing soils of similar constitution under similar conditions, the biological production of carbon dioxide is governed by so many factors that it is scarcely possible that it can be used as a general measure of fertility.

The carbon dioxide produced in the soil from the biological decomposition of organic matter and from the respiration of plant roots constitutes the principal agency whereby the supply of this constituent, depleted by photosynthesis, is regenerated in the atmosphere. It is also of importance as a constituent of soil moisture and of percolating waters, and thus contributes to the formation of soil by intensifying the hydrolytic action of water on mineral silicates.



Fig. 12. The effect of aeration on plant growth.  
(Reproduced from *Soil Conditions and Plant Growth* by courtesy of Sir E. J. Russell and Messrs. Longmans Green & Co. Ltd.)



CHAPTER 12



*Soil Acidity and Lime Practice*

**Soil Acidity** is described by various terms, such as hydrogen-ion concentration, reaction, pH values, or exchange acidity. Each of these terms refers to a measurement of acidity in some form. In regions of low rainfall where leaching has not been excessive, acid soils are infrequent. In such regions the opposite of this, alkaline condition, frequently develops. The so-called black alkali soils result from the accumulation of bases in a soluble form. Throughout the regions of moderate rain-fall some moderately acid soils are found, and others are neutral or alkaline, depending to a considerable extent on the character of the parent material. In regions of high rainfall soils are usually acid to varying degrees unless their parent material is highly calcareous, and even then strongly acid soils are frequently found with underlying calcareous material only 3 or 4 feet, or even only a few inches, from the surface. A nearly neutral or slightly alkaline soil is frequently considered the best for agricultural purposes ; however, no broad statement of this kind is justified.

Acidity may be defined as a condition in which the concentration of hydrogen ions is greater than that of hydroxyl ions. Neutrality is the point at which the concentration of  $H^+$  ions exactly balances that of the  $OH^-$  ions, a condition found in pure water. Alkalinity is the state in which the concentration of  $OH^-$  ions is greater than that of the  $H^+$  ions. In the soil more or less soluble mineral matter, decaying plant residues, colloidal clay, and organic matter are in constant contact with the soil solution, all in an ever-changing state. There is produced as a result, a condition of extreme complexity.

Soils and soil materials originally varied greatly in their content of basic material. These are gradually lost in the form of bicarbonates or other salts as a result of the reaction of carbonic or other acids with them. The simple reaction between carbonic acid and calcium carbonate may be cited as representative.

**The Nature of Soil Acidity.**—Soil acidity has been regarded as

being of two kinds. These are *active* and *reserve*, or *potential*, acidity.

(1) *Active acidity*.—Active acidity represents the extent of excess in concentration of  $H^+$  ions over that of the  $OH^-$  ions in the soil solution. This excess may cause a high degree or intensity of acidity and yet not require the addition of much basic material for its complete neutralization.

Active soil acidity is expressed in pH units, in which 7 represents neutrality, or perfect balance between  $H^+$  ion and  $OH^-$  ion concentrations. The pH readings 6.0, 5.0, 4.0, 3.0, represent increasing acidity, respectively. At pH 5.0, the acidity is 10 times as great as that at 6.0; at 4.0, 100 times; and at 3.0, 1,000 times as great as that at 6.0. Alkalinity is represented by numerals that are larger than 7.0, such as 7.5 and 8.0. These relationships, it should be noted, are not arithmetic but geometric.

Ranges in pH of below 5.0 to a little above 7.0 are found rather commonly in humid soils, and readings below 3.0 have been reported as well as some above 8.5. Normally, the extreme range in soils of humid regions, however, is between a little under 4.0 and somewhat above 8.0.

(2) *Reserve, or Potential, Acidity*.—The reserve, or potential, acidity of soils represents the H ions held in the colloidal matter of the soil. These ions are not so free to move as are those in the soil solution, but they are in equilibrium with them. The importance of the reserve acidity is this. If lime is added to a soil, its active acidity is quickly neutralized. After this has occurred,  $H^+$  ions come out of the colloidal complex and in time give the soil moisture an acid reaction again. This supplying of  $H^+$  ions to the soil solution explains the extreme importance of the reserve acidity.

It is the reserve acidity and its correction with which the farmer is concerned. He applies limestone to the extent of 1 to 2 tons per acre or more (varying with the fineness of grinding) in order to neutralize the active acidity as H ions come into solution out of their colloidal hiding place. The amount of active acidity in heavy soils is negligible in comparison with that of the reserve acidity. A fairly definite relationship exists between these two types of soil acidity.

#### CAUSES OF SOIL ACIDITY

The main factors in soil acidity are :—

- (1) The extent of leaching.
- (2) The origin of the soil humus.

(3) The use of certain fertilizers.

(4) Micro-biological action.

(1) **The Extent of Leaching.** The extent of leaching is the main factor involved in determining whether or not the soil formed will be acid. Extent of leaching is determined largely by rainfall, age of soil, temperature, and vegetation. Of these, rainfall is in general the most important, and regions having an annual rainfall of 25 inches or more usually have a high percentage of acid soils.

(2) **The Origin of the Soil Humus.** Peats when formed in basins receiving drainage waters charged with alkali and alkaline earth carbonates are of course non-acid, since the organic exchange material formed from plant residues under these conditions becomes saturated with bases as fast as it is formed. Under other conditions, when the rate of inflow of basic compounds is insufficient to keep pace with the formation of organic exchange material, this material is left in an acid condition.

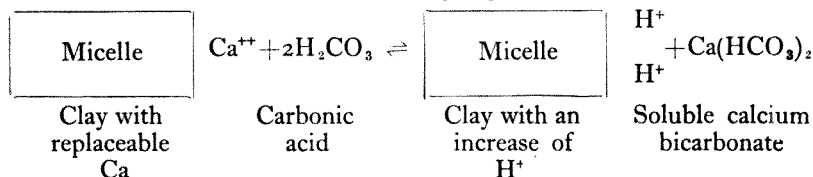
(3) **The Use of Certain Fertilizers.** The use of certain fertilizers has long been known to increase soil acidity. In this connection, ammonium sulphate has received considerable attention. When it nitrifies, two acid products result—nitric and sulphuric acids. These are both soluble and thus make the soil solution more acid, also increasing its tendency to remove bases from the exchange material so as to form soluble salts. The soluble salt may be absorbed by plants or removed in the drainage water. In either case, the exchange material has lost some base and the soil as a whole is just that much more acid. Ammonium nitrate acts similarly, while calcium cyanamide and sodium nitrate have the opposite effect. Pierre has investigated the acid and base balance that results from the application of various fertilizer materials and fertilizer mixtures to soils, and has proposed a method for its determination in a sample of the fertilizer. Largely as a result of this work, much attention is now being given to compounding fertilizers that will have the most favourable reaction effect for any particular soil or condition.

(4) **Micro-biological Action.** In the soil sulphuric, nitric, and carbonic acids are constantly being formed through biological activity. These on liberation immediately seek a base, and if the base exchange material is well saturated, they obtain it, become neutralized, and the soil solution remains neutral or nearly so. If the base exchange material is low in base saturation—that is if it is distinctly acid—then these acids do not become completely neutralized, and

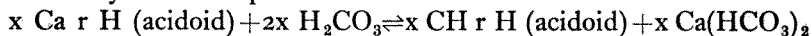
being soluble, they cause the soil solution itself to become acid in direct proportion to the acidity of the exchange material.

### THEORY OF SOIL ACIDITY

Consider a representative humid region soil, rather high in replaceable calcium, as functioning under optimum conditions of moisture and temperature. Naturally a considerable amount of  $\text{CO}_2$  is evolved as the organic matter decomposes and the presence of carbonic acid ( $\text{H}_2\text{CO}_3$ ) in the soil solution is inevitable. The ionic hydrogen thus generated is exceedingly active and will tend to replace the exchangeable calcium of the colloidal complex. This occurs not only because of mass action effect but also because ionic hydrogen is adsorbed more strongly than is the ionic calcium. This reaction may be shown graphically as follows, for simplicity only one of the adsorbed calcium atoms being represented in action :



This adjustment is very simple, almost instantaneous, and the interchange of calcium and hydrogen molecularly equivalent. And if the soluble bicarbonate is removed by drainage, as commonly occurs in humid regions, the movement of the lime will be continuously outward. Because of this phenomenon, calcium becomes the most active metal of the soil and the metal most largely lost in drainage. Moreover, the continual adsorption of  $\text{H}^+$  by the colloidal clay at the expense of the calcium tends by equilibrium to increase the  $\text{H}^+$  ion concentration of the soil solution and the pH of the soil is gradually lowered. This illustration emphasizes not only the tremendous loss of lime to which most soils are subject but also indicates why humid region soils tend to become acid. The phenomenon may now be expressed as follows :



It is not to be inferred that the active hydrogen in nature does not replace cations other than those of calcium. But because the exchangeable calcium ions are especially numerous on the outer and more exposed surfaces of the micelle they are more easily released. Thus in almost every normal soil, calcium is replaced by the natural process explained above to a greater extent than is any other cation.

The reversibility of an exchange reaction has been mentioned. If lime is applied to an acid soil, that is, one in which the colloidal complex is definitely dominated by hydrogen, a replacement, the reverse of the one just cited, readily occurs. The active calcium ions by mass action replace the hydrogen and often other cations as well. As a result the clay becomes higher in exchange calcium, the pH is raised, and the whole physiological set-up of the soil is modified.

**Relationship between Soil Reaction and Exchangeable Calcium.** Since calcium amounts to about 80 per cent. of the reaction value of the exchangeable bases in soils, a close relationship should exist between the reaction, as shown by the pH value, and the exchangeable calcium, in soils with the same type of colloidal complex present in approximately the same proportions.

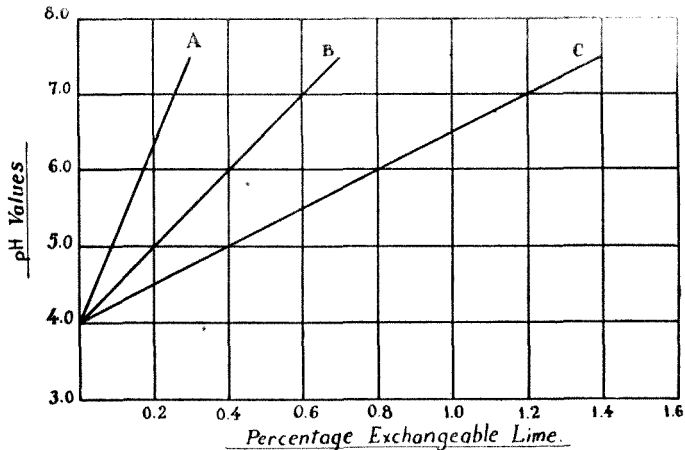


Fig. 13. Relationship between pH and exchangeable lime for different soils. A: Sandy soil; B: Heavy loam; C: Peaty loam.

Although, among soils of similar composition, there is an obvious relationship between the reaction of the soil, as expressed by its pH, and its content of exchangeable calcium oxide, a general expression for this relationship is not easily obtained, since the acidic properties of a soil vary not only with the relative proportions of mineral and organic matter in the colloidal complex, but also with the composition of the mineral absorbing complex. Whilst the pH of base-unsaturated organic matter may be 4.0 or even less, that of the so-called acid clay is rather higher and depends ultimately on the relative proportions of acid ( $\text{SiO}_2$ ,  $\text{P}_2\text{O}_5$ ) and basic ( $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ) groups present. Clay colloids rich in silica, such as those of bentonite and certain alluvial

clays will be more acid when desaturated than are clay colloids rich in sesquioxides, such as those of laterites and tropical red earths.

It should be noticed that soils may be equally acid, i.e., have the same pH, and yet contain differing amounts of exchangeable lime (Fig. 13). Therefore, the determination of the pH of a soil, although it tells us something about the intensity of the acidity, does not necessarily tell us how much exchangeable lime is actually present. Actually it is the exchangeable lime that really matters and pH does not tell us much about that. However, if we are dealing with soils that we know fairly well, a knowledge of the pH may give us some help.

#### **Quantitative Methods for Determining Soil Acidity.**

Apparently the first report of an attempt to devise a quantitative method for determining soil acidity was made by Tacke in 1897. Working with peaty soils he mixed calcium carbonate with a sample of the soil moistened to paste, and then determined the carbon dioxide evolved, which was taken as a measure of the acidity present in the soil. A number of methods based on a similar principle were proposed during the first 15 or 20 years of the twentieth century. The main objection to this type of method is the slowness and indefiniteness of the reaction involved.

In another class of methods proposed, the soil is treated with a known excess of alkaline hydroxide or bicarbonate in solution, after which the excess over that which reacts with the soil acids is determined in various ways and the acidity calculated by difference. These methods have been of considerable use, but some are rather cumbersome and give results of doubtful value. The Veitch lime-water method may be classed in this group. It is a method for determining the amount of limewater required, on evaporation with a soil sample, to give a subsequent water extract of the soil sample a slightly alkaline reaction. The method is one of the oldest and was formerly used quite extensively.

In still another class of methods, the sample of soil is treated with a neutral salt solution, thus allowing for cation exchange between the salt and exchangeable material of soils. The salt solution then becomes acid and in accordance with the acidity of the exchange material. After filtration, the acidity of the salt extract is determined by titration. Since the reaction involved does not go to completion, a factor is then sometimes used to calculate the total acidity of the soil. The Jones calcium acetate method and

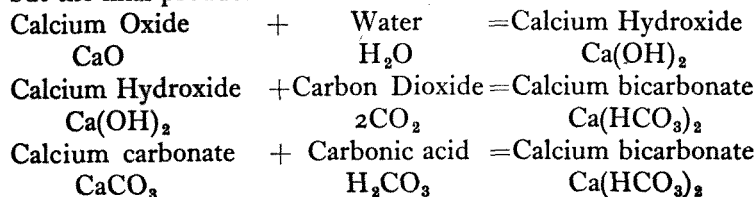
Hopkins' sodium chloride method are examples of this class of methods, which were formerly used quite extensively.

Much attention has been given in the past 20 years to the perfection of an electrometric method for the accurate determination of the pH value of soils. The hydrogen electrode method was first used, but being rather cumbersome, was later superseded quite generally by the simpler quinhydrone method. This method was extensively used, but with a few special soils gives inaccurate results and in the alkaline range especially is none too accurate. Within recent years, the glass electrode method has reached a high state of perfection and is now accepted as the standard by the International Society of Soil Science for the determination of the pH value of soils. By this method active acidity is determined in pH units. Precise determinations are made with the potentiometer. The sample of soils to be tested is shaken with a small quantity of water and allowed to stand in contact with the electrodes until equilibrium is established. The electrical potential readings are then made, and the pH of the soil is calculated.

**Soil Moisture and Determination of pH.** Soil moisture content should be considered in studies involving the pH values of soil. Ludi has shown that, variations over a year on the pH of forest soils amounted to about 1 pH unit. The variations were irregularly distributed throughout the year, although there were some indications of a minimum acidity in spring and a maximum in mid winter. It has been found by Haas that moisture markedly affects the pH values of soils. Few orchard soils reacted alkaline after the moisture content has been considerably reduced.

Evidence was obtained by B. Singh and G. Mitra, that plants altered the H-ion concentration of soil and cultures to their own requirements provided that the initial pH lay within a given limit.

**Action of Lime in the Soil.** Lime in any of the regularly used forms reacts rather quickly with moist, acid soils. The three forms, oxide, hydroxide, and carbonate, react somewhat differently ; but the final product is the same.



It should, of course be appreciated that in addition to these conventional reactions numerous complex reactions with the materials held in the colloidal matter occur simultaneously.

### CORRECTION OF ACIDITY

As already stated, acidity is the result of the accumulation of an excess of  $H^+$  ions over the  $OH^-$  ions. The bulk of the  $H^+$  ions are held in close association with the colloidal matter. When a form of lime is added to a moist soil, part of the calcium becomes ionized and is represented as  $Ca^{++}$ . Calcium, magnesium, sodium, potassium, and ammonium ions or cations, as we already know, have the power of changing places with each other or with hydrogen in a colloidal complex such as that in the soil.

After an application of lime to moist soil, the soil solution becomes charged with  $Ca^{++}$  ions. Being active, they soon change places with  $H^+$  ions in the colloidal complex. The  $H^+$  ions are released into the soil solution where they unite with  $OH^-$  ions and form water. In time, many of the  $H$  ions are replaced by the  $Ca^{++}$  ions : and the colloidal clay, then being dominated by calcium, is no longer acid. In other words, the acidity of the soil has been neutralized or corrected for the time being. Because of the continued generation of  $H^+$  ions which displace  $Ca^{++}$  ions in the colloidal material, the  $H^+$  ions eventually make the soil acid again.

Any base-forming material might be used to reduce the  $H$ -ion concentration of soils. Calcium and magnesium compounds because of their abundance and ease of accessibility in many areas are generally used for the purpose of controlling soil acidity.

**Kinds of Lime in use.** The term *lime*, although admittedly not entirely correct, is used for the materials applied to soils for correcting acidity, regardless of their chemical composition.

Carbonates, burned lime, hydrated lime, and a few other by-product materials are used on the soil.

**Comparative Effects of Different Forms of Lime.** The  $OH^-$  and the  $CO_3^-$  ions are the active agents in liming materials. The effectiveness of limes, therefore, is closely correlated with the total quantity of these anions present. This statement is, of course, based on the assumption that the carbonate forms are of suitable fineness. Some allowance may be made for the more rapid action in the soil by burned and hydrated, as compared with the carbonate forms.

**Application of Liming Materials.** Limestone corrects acidity rather slowly. The finer ground stones, however, act more rapidly than do the coarser ones. Burned and hydrated limes act more quickly than do the carbonate forms. In fact, in moist soils, burned and hydrated limes may do their full work in a few days.

Because the effect of lime is distinctly the result of contact between the lime and the soil, thorough mixing with the soil is essential for good results. And for this reason a finely ground limestone gives quicker effects because of the large surface in contact with the soil. Moreover, the fine limestone consists of many particles which if well mixed with the soil constitute many centres of alkalinity. This condition is desirable because lime does not move readily or quickly over considerable distances in the soil. Even downward movement through the soil in the field is very slow.

Ground lime can be spread by a manure distributor, but this may be an unpleasant and even dangerous proceeding, owing to the blowing about of the highly caustic lime dust. There are also great dangers in the storage of ground lime in bags. Added to these disadvantages is its high price relative to lump lime. Limestone when finely ground, is as effective as lime and the only disadvantage is that nearly twice as much must be used to supply as much lime as an equal weight of quicklime. (56 parts CaO = 100 parts CaCO<sub>3</sub>). The advantages of ground limestone are that it is harmless to the clothing or persons or workmen ; it does not need to be slaked ; if wetted, it becomes powdery again on drying, and it can be stored in buildings without risk of heating and fire.

It is generally supposed that limestone, in order to be as effective as lime, should be very finely ground. A product with about 80 per cent. passing a 100-mesh sieve is often prescribed. But, from recent work, it appears that a coarser product would serve the purpose. A ground limestone of grade finer than 20-mesh (about 1 mm. to dust) would contain sufficient fine material for immediate reaction, whilst the coarser fractions would react with the soil in subsequent years.

Sprague determined the quantities of hydrated lime (from 1½ to 1¼ times as much of finely ground limestone) required to change the pH of a wide range of soil textures. His data are given in Table 20.

**Overliming.** Considerable additions of lime to soils of fairly high acidity suddenly change the relations between the H and OH

ions in the soil. Soil organisms tend to adjust themselves to existing conditions, including the pH. Sudden changes, therefore, require quick adjustments. Moreover, the solubility of iron, aluminium, and manganese tends to be relatively high in acid soils. Excessive liming renders all these and other elements less soluble so that plants temporarily may not obtain an adequate supply of them, and retardation or stoppage of growth and reduced yields may result.

Some dangers attend the making at one time of single applications to acid soils of 3 to 5 tons or more of finely ground limestone to the acre. These quantities of coarsely ground limestone, however, are unlikely to cause trouble. If the stone contains a considerable quantity of fine material, the reaction may be brought to pH 7.0 or higher. High alkalinity may render iron and the trace elements insoluble and deprive plants of them. Reduced yields of acid-tolerant crops may follow.

TABLE 20

*Pounds of Hydrated Lime required to Reduce Soil Acidity to the Desired Extent.*

Soil Acidity expressed in pH values	Lime, pounds per 1,000 sq. ft. <sup>1</sup>			
	Light sandy soils	Medium sandy loam soils	Loam and silt loam soils	Clay loam soils
pH 4.0 ... ..	60	80	115	145
pH 4.5 ... ..	55	75	105	135
pH 5.0 ... ..	45	60	85	100
pH 5.5 ... ..	35	45	65	80
pH 6.0 (2) ... ..	None	None	None	None

(<sup>1</sup>) Multiplying these figures by 43 gives approximately the corresponding application on the basis of an acre.

(<sup>2</sup>) Acidity at pH 6.0 is so slight as not to be objectionable.

**Effects of Soil Acidity on Plants.** A good deal of attention has been given to the relationship of crop yield to the hydrogen-ion concentration of the soil. The acidity of soils generally varies between pH 3.5—4 in the most acid soils, and pH 9—10 in the most alkaline. The pH of any one soil tends to remain fairly constant since the buffering effects of the silicates, humates, phosphates, etc., reduce its susceptibility to minor influences. Only relatively drastic treatment such as the addition of dressings of lime or calcium carbonate, and the extensive and continued use of ammonium sulphate will bring about any great changes. It is

manifestly important, therefore, to know how various crops thrive in soils of particular hydrogen-ion concentrations and what crops thrive best at any particular pH value. One very thorough investigation is that made in Sweden by Arrhenius, who grew a large number of farm crops in soils of varying pH values, and was able to show that there is for any particular crop a pH range over which, under the conditions of the experiment, the particular crop thrives best. The following are a few of Arrhenius' results :

TABLE 21

Crop	pH
Wheat ... ..	6.5—7.5
Sugar Beet ... ..	7.0—7.5
Barley ... ..	7.0—7.5
Turnips ... ..	5.8—6.8
Rye ... ..	5.0—6.0
Swedes ... ..	4.9—5.5
Potatoes ... ..	4.8—5.7

It must be understood that these are the findings of one set of experiments, and the results are not of rigorous and universal application. Under different conditions of climate, soil texture and so forth, the results of such experiments may well be appreciably different.

The view is held nowadays that it is rather the conditions in the soil, brought about by the presence of acidity, which are detrimental to plants. Among factors thought responsible for this toxic effect are :—

(1) Influence of pH differences on the permeability of cations through the plant membranes.

(2) Entry of acid into roots of plant from acid solutions around.

(3) Inhibition of enzyme processes, as enzymes are particularly sensitive to pH changes.

(4) N enters the plant as  $\text{NO}_3^-$  and is converted to  $\text{NH}_3$  before reaching the stem. Disturbance of this process will affect the ability of the plant to produce green tissue.

(5) Disturbance of the balance of minerals passing through the root membrane where an ionic equilibrium exists. This will affect the plant metabolism.

(6) Toxicity due to the presence of  $\text{Al}^{+++}$  in soil solutions under very acid conditions.

However, the relative effects of hydrogen ions and aluminium

ions in the soil are still very much disputed. It has been argued that since the titration curve of an aluminium salt and an alkali shows that aluminium ions cannot exist in solution at a hydrogen-ion concentration less than that corresponding to  $\text{pH}=4$ , they cannot exist in any but the most acid soils. It does not follow, however, that the hydrogen-ion concentration at which aluminium is precipitated is any clue to what happens under soil conditions where organic matter and other factors have important effects. It has also been very much argued that practically no aluminium is found in the water extract of most sour soils, but it must be remembered that very little of any of the active soil cations are found in an aqueous extract.

#### **Effects of Soil Acidity on Availability of Phosphorus.**

Phosphorus is most readily available to plants in the zone of slight acidity and becomes less readily available with increasing concentration of H ions. In the zone of high acidity, soluble phosphorus combines with compounds of aluminium and iron, forming highly insoluble aluminium and iron phosphates. In these compounds, phosphorus is only very slightly available to plants. On the alkaline side, phosphorus combines with calcium, forming tricalcium phosphate. Though not readily available to crops, phosphorus in this form is much more so than in aluminium and iron compounds.

V. Vincent found that about 80 per cent. of the total soil phosphorus may be in an organic form in acid soils and that its mineralization by bacteria is favoured by liming. It exists in the form of decomposable esters derived from plants, in other forms difficultly soluble in water (more in basic than acid solutions), and in practically insoluble forms.

A possible explanation for the toxicity of plants grown on acid soils was suggested in recent years by G. W. Robinson and others. They suggested that injury results not directly from acidity but from low ratio of calcium to other ions. Robinson has found that in Wales there is little response to liming in soils where the "exchangeable calcium" (expressed as CaO) is above 0.3 per cent. even though the soil may show a considerable acidity. Pearsall has found plants usually indicative of acid soils—as for example "Nardus" and "Calluna"—growing on stream gravels in the Lake District where the water was approximately neutral but has a low ratio of calcium and magnesium to potassium and sodium ions.

## CHAPTER 13

### *Soil Alkalinity and Reclamation of Alkaline Soils*

ALKALINITY in soils occurs most commonly, but not exclusively, under arid climates. It is attributed either to the presence of an actual excess of sodium salts, or to the predominance of sodium among the exchangeable bases—the latter a consequence of the former presence in the soil of sodium salts. In some cases, potassium salts may be present in appreciable amounts, but it is unusual for soils to occur in which potassium is the dominant exchangeable base.

Baron Berthollet, one of the greatest luminaries of French Science, who accompanied Napoleon in his Egyptian expedition towards the end of the 18th century, was struck by the fact that solid sodium carbonate existed on the banks of the Nile. Being one of the originators of the law of mass action, Berthollet believed that the sodium carbonate was formed by the interaction of sodium chloride obtained by the flooding of the Nile and the calcium carbonate present in the soil. This hypothesis was supported by Hilgard and his colleagues in California, who were pioneers in the reclamation of alkali soils in the United States.

**Hilgard's View.** As is well known, Hilgard devoted extended study to the origin and mode of accumulation of the soluble salts in soils, to the tolerance for plants of the soluble salts that occur in alkali soils, and to methods of alkali soil reclamation. He found that the soluble salts are chiefly chlorides, sulphates, carbonates, and the bicarbonates of sodium, and that these salts arise, either directly or indirectly, through the natural weathering process to which rock masses are subjected in the state of nature. The ratios of the different salts vary widely from place to place, and the effects produced on plants by different salts also vary greatly. Hilgard found that sodium carbonate is extremely toxic, sodium chloride

somewhat less so, and sodium sulphate still less toxic. Hence special emphasis was placed on the soluble anions of alkali soils.

When the soluble salts have been removed, as by leaching, Hilgard believed that an alkali soil would be restored to a normal state. He recognised, however, that the physical properties of alkali soils are sometimes extremely adverse. This was attributed to the deflocculating effect of sodium carbonate. If sodium carbonate is present, he held that it may be necessary to apply gypsum, or some substance which produces similar effects, before it is possible to leach out the soluble salts. He assumed that the chemical effect of gypsum would be that of the well known chemical reaction that takes place when a soluble calcium salt is added to a solution of sodium carbonate as follows :—



Thus upon applying gypsum the alkaline and therefore the deflocculating sodium carbonate will be converted into insoluble calcium carbonate and neutral sodium sulphate ; consequently, the soil will become flocculated and then the soluble salts can be effectively leached out.

**Present View.** Despite the importance of Hilgard's work investigation in recent years has established the fact that an additional factor, not recognised by him, also plays an important part in many alkali soils. The reference here is to the chemical reactions and physical effects that are produced in the soil by soluble salts. Sodium salts may react chemically with the clay and humus of the soil and produce a condition which in itself is harmful to crops and which must be overcome before the soil can be said to be reclaimed. He was impressed by the fact that calcium chloride is obtainable in the aqueous extract of a soil situated near the sea. And he believed that it must have been formed by the action of sodium chloride on the soil. He tried to explain what happened to the sodium, which did not exist in the soluble state. In order to test this point, he treated the soil with a solution of sodium chloride in the laboratory and could obtain calcium chloride and an insoluble sodium compound. When calcium chloride is removed by washing, the insoluble sodium compound is easily decomposed by the action of carbonic acid forming sodium bicarbonate and carbonate. By the successive interaction of sodium chloride, water, carbonic acid, and water again, he was able to obtain 100 grams of sodium carbonate

from 1 kg. of soil. These experiments can be very readily reproduced and prove, therefore, that the sodium chloride does not react with calcium carbonate as was assumed by Berthollet, but it reacts with the soil forming a sodium absorption complex and calcium chloride, which can be removed by washing. The sodium absorption complex can be decomposed by carbonic acid with the formation of sodium bicarbonate and carbonate. The explanation of Paul de Mondesir has been developed and supported by the well-known Russian exponent of soil science, Dr. Gedroiz, Professor W. B. Kelley in America and Professor J. de Sigmond in Hungary.

Gedroiz, Hissink, de Sigmond, Cummins and Kelley, de Domenicis and others have found that base exchange has also an important effect on the physical properties of the soil. According to Gedroiz the pronounced deflocculation that develops upon leaching Na-saturated soil is due to the  $\text{OH}^-$  ions that are formed through hydrolysis. He concluded that the consequence of this deflocculation is the gradual development of peculiar morphological structures within the soil profile. Since leaching a sodium saline soil promotes the formation of sodium carbonate and produces adverse physical effects on the soil, Gedroiz concluded that leaching may produce actual injury rather than benefit to the soil.

Thus it is evident that Gedroiz has placed special emphasis on the cations of alkali soils, whereas Hilgard placed the emphasis on the soluble anions.

The fact that Gedroiz in Russia, and Kelley and his collaborators in America, reached the same conclusions as de Sigmond did in Hungary, indicates that this process (which we may call alkanisation) is very widely spread over the alkali regions of the world. The reaction itself is a simple base exchange, which takes place between the sodium cations of the soluble salts and the absorbed cations, chiefly calcium, of the original alkali-free soil. Since this exchange reaction is more complete when the sodium salt solution is concentrated, it is evident that alkanisation is favoured by arid rather than by humid climates.

### ORIGIN OF ALKALINE AND SALINE SOILS

The first pre-requisite for the occurrence of alkaline and saline soils is the presence of sodium salts in the soil or the parent material. These salts originate usually from underground water in situations where the water-table is relatively near the surface. Such con-

ditions generally occur in areas of basin-shaped topography. The salts may have originated directly from the chemical weathering of silicates, resulting in the accumulation in the underground water of the soluble products of hydrolysis, or they may represent the vestiges of former seas or salt lakes. Stated generally, the most usual mode of origin is from saline ground waters, either in the vicinity of inland seas or salt lakes, or in depressions where the water-table is at or near the surface. In such cases there has usually been a change in the hydrological conditions.

Another factor, thought by certain soil scientists to be essential to the development of alkali soil, is the occurrence of an impervious stratum in the subsoil, the presence of which prevents deep penetration of excess water and makes possible a high ground-water level where none would otherwise exist.

The reason why a high water table is conducive to the formation of alkali soil in arid climates, whereas this is not the case in humid climates, is threefold :—

- (1) ground water in arid regions usually contains very much more dissolved salts than in humid climates ;
- (2) the rate of evaporation is much greater in arid climates ;
- (3) the precipitation in arid regions is insufficient to leach the soluble salts, which rise during the periods of intensive evaporation between rains, back into the ground waters whence they came.

Consequently, the soil of dry regions tends to become increasingly saline as long as the ground water remains within capillary reach of the evaporation surfaces.

The rate at which salts accumulate in the soil depend upon three factors :—

- (1) the rate of capillary movement of water through the soil ;
- (2) the rate of evaporation ;
- (3) the salt content of the ground water. ✓

✓ **Saline Soils.** Saline soils are the white alkali soils of the earlier American writers, and the solontshak soils of the Russian school. They contain an excess of sodium salts, generally the chloride or sulphate, and have a flocculated structure. They occur usually in depressions, and the distribution of salts varies with the season. During drought, they show white efflorescences of sodium chloride or sulphate, from which the American term white alkali is derived. During rain, the salts deposited at the surfaces are

dissolved and temporarily washed down towards the water-table. Saline soils occur most commonly in arid, semi-arid, and semi-humid regions, and may represent modified chernozems, chestnut earths or grey earths. Where the water-table lies so near the surface as to maintain permanently moist conditions, saline peaty or saline meadow soils may result.



Fig. 14. A tract of saline soils in lower Egypt.



Fig. 15. Saline soils in "Paris" area near the Kharga oasis in the southern desert of Egypt.

**Alkaline Soils.** Alkaline soils, on the other hand, are characterized by the presence of sodium carbonate. They are termed black alkali by the American workers and solonetz by the Russians. The saline soils are in a state of flocculation but the

alkaline soils have a strongly alkaline reaction and are deflocculated ; sodium is the predominant cation in the colloidal complex.

**Physico-Chemical Properties of Alkaline Soils.** In recent years great attention has been paid to the effect of absorbed sodium on the physical and chemical properties of soils.

Laboratory research by numerous investigators has shown that sodium absorbed by the clay complex of soils increased dispersion, pH values, swelling, osmotic imbibition, migration velocity, apparent density of puddled soils, and the hardness of dry aggregates ; and lowers heat of wetting, sticky point, and permeability.

The effect that absorbed sodium has on soil characteristics is related to the amount and character of the clay of the soil, to the extent to which other ions are replaced by sodium, and to the extent to which flocculating electrolytes are removed.

Changes occurring in absorbed bases, micro-aggregate analysis and  $H_2O$  suction curves also proved most suitable for determining the effect of amelioration in alkaline soils.

The ratio of Na to Ca, or of univalent to bivalent bases in the exchange complex of alkali soils, has been also suggested as a measure of their unsatisfactory properties and the dispersion co-efficient may be used for determining the relative amounts of exchangeable Na and Ca.

**Hydrolysis of Na-Clays.** As Cumins and Kelly pointed out, the extent to which Na-clay undergoes hydrolysis in pure water is limited by two factors, namely, the low ionization of water and the concentration and composition of the soluble sodium salts that are present. Theoretically we would expect that at the equilibrium point of this reaction the ionization constant of the sodium-clay would equal that of the NaOH formed. Since the former is relatively low, the total concentration of NaOH will also be low. However,  $CO_2$ , which is normally present in soils to some extent, exerts a potent influence, first through increasing the ionization of water and secondly through converting NaOH into  $NaHCO_3$ . Thus carbonated water will be more effective than pure water in the conversion of Na-Clay into H-Clay.

**Deflocculation of Na-Clays.** Various theories have been proposed to explain the deflocculation of Na-clays. The most generally accepted view is that  $OH^-$  ions, formed by hydrolysis, cause dispersion of the soil particles. However, the behaviour of soil colloids saturated with different bases, as revealed by studies

with the use of the petrographic microscope, suggests that some additional factor is involved.

**Solodi or Soloti Soils.** Gedroiz and de'Sigmond hold that when sodium saline soil is subjected to prolonged leaching, there is developed first the solonetz structure, and later the solodi, or degradation condition, the latter denoting that the base exchange complex has more or less been decomposed. However, when the soil contains calcium carbonate, Gedroiz concluded that leaching would not produce decomposition of the inorganic constituents of the base-exchange complex except to a very limited extent. Kelly's work indicates that the base-exchange complex of the soil containing calcium carbonate undergoes no important decomposition upon leaching. This must be true, since H-clay formed by hydrolysis of Na-clay will immediately react with calcium carbonate and thus be converted into stable Ca-clay.

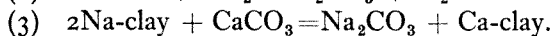
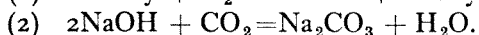
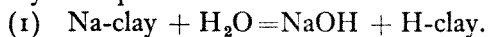
However, the process of solodization is more or less analogous to podsolization (*see* Chapter 21), in that a part of the absorbed bases of a soil are replaced by H ions in both bases, but degraded alkali soils differ from podsol soils in two important particulars; firstly, the former contain relatively large amounts of absorbed sodium, whereas the latter contains almost none; secondly, the absorption complex tends to undergo decomposition as a result of both degradation and podsolization with the consequent formation of colloidal  $\text{SiO}_2$ , and according to Gedroiz,  $\text{SiO}_2$  of silicates is leached out of podsol soils, but tends to accumulate in degraded alkali soils.

**Relationships of Saline to Alkaline Soils.** There is no hard and fast line of division between saline and alkaline soils, and all stages in the transition between the two types may be encountered. This, in addition to the great variety of possibilities in the conditions antecedent to salinization, results in very great variation in the character of these soils. The principal factors, are however, the position of the water-table, the composition of the ground-water, the nature of the soil and the degree of leaching, either naturally by rainfall or artificially by irrigation.

However, the relationship of alkaline to saline soils is now intelligible, owing to the investigations of Gedroiz, De Sigmond, Kelly and others, on the basis of base exchange reactions of these soils. As mentioned before, the presence of an excess of sodium salts in saline soils result in the partial or complete replacement of their exchangeable calcium by exchangeable sodium. So long as

excess of sodium salts is present they remain in the flocculated condition with neutral or slightly alkaline reaction. With removal of excess sodium, the reaction becomes markedly alkaline and deflocculation occurs.

It should be remarked that, although the presence of sodium carbonate is a characteristic of alkaline soils, the development of their distinctive properties is not dependent on the occurrence of large proportions of this salt. If, by the continued action of sodium salts, a soil is brought to the state in which the exchangeable calcium is replaced by sodium, the resulting sodium is potentially an alkaline soil and becomes deflocculated as soon as the concentration of the excess salts falls sufficiently low to permit the hydrolysis of the sodium humates and aluminosilicates. Under these conditions, sodium carbonate may be formed either by the reaction of the sodium clay with calcium carbonate, or by the action of carbon dioxide on the sodium hydroxide, liberated by hydrolysis. These reactions may be represented by the equations :—



Sodium carbonate should thus be regarded as one of the consequences of alkalization rather than as the cause of the distinctive characters of alkaline soils. The percentage of sodium carbonate is in itself no measure of the degree of alkalization of a soil. If carbon dioxide be excluded, it is possible to prepare completely deflocculated soils from which sodium carbonate is entirely absent.

**Soil Dynamics in the Evolution of Alkaline Soils.** The conceptions of "soil dynamics" has recently come into common use, in fact Stebut has made it the basis of his book on soil science. This expression "soil dynamics" summarises all the changes, chemical, physical and biological, that are continually occurring in soil, such as those caused by weathering, leaching, salt accumulation, drainage, evaporation and by the whole soil population. The expression is convenient as illustrating the fact that there is no stability in soils, except in exceptional circumstances. A continual evolution, indeed, goes on in the soil, changing it from the lifeless rock from which it originated. It is this dynamic character of soils that makes the elucidation of their reaction to reclamation measures so difficult. Unless the new treatment of the soil changes the soil dynamics in a way that will lead to a normal agricultural soil, the

reclamation, although possibly temporarily effective, will not be complete, and the reclaimed soil will deteriorate again.

**Evolutionary Stages of Alkaline Soils.** The evolution of alkali soils may be considered as taking place in four stages, namely, salinisation, alkalisation, desalinisation, and degradation. Gedroiz has fully discussed the various influences of Na-absorption compounds on the genetics of alkali soils. De Sigmond has emphasised the dynamic aspects of saline and alkaline soils.

(a) *Salinisation.* Salinisation obviously denotes the process of soluble salt accumulation as such.

(b) *Alkalisation.* Alkalisation refers to the formation of Na-absorption compounds through base exchange; and the so-called alkalisation of the absorbing complex of the soil takes place concurrently with the salinisation process. The accumulation of soluble salts in soils is a gradual process, in most cases at least, and it is well established that the rate of the base exchange reaction is extremely rapid. It is, therefore, certain that more or less alkalisation of the absorbing complex takes place immediately upon contact between the soluble salts and the soil. The mere accumulation of soluble salts in the soil is not the only important aspect of the alkali soils, and it is therefore extremely important to understand the reactions between soluble sodium salts and the base exchange complex of the soil. The failure to recognise this fact imposed the chief limitation on Hilgard's comprehension of alkali soils.

It is also equally important to emphasise the fact that the alkalisation of the absorption complex of the soil is greatly influenced by the composition of the soluble salts. The presence of soluble calcium salts tends to prevent the formation of Na-absorption compounds. Least alkalisation is possible if the soluble salts that accumulate in soil contain a higher proportion of Ca in relation to Na. There are many important areas of alkali soils in Sind (India), California (U.S.A.) and Egypt that contain no more than negligible amounts of absorbed sodium. Such soils always contain a high content of soluble calcium salts and will become essentially healthy when the excess of soluble salts is leached out. They may be readily reclaimed by drainage and flooding.

(c) *Desalinization.* Desalinization refers to a process in which certain alkali soils on leaching are subjected to a constitutional change. Gedroiz has discussed this aspect of the subject at considerable length. For convenience the desalinization process may be

considered as taking place in three stages, namely, the removal of soluble salts; the formation of  $\text{Na}_2\text{CO}_3$  through hydrolysis of the absorption complex, either in the presence or absence of  $\text{CaCO}_3$ ; and the dispersion of the soil particles with the consequent elutriation downwards of the finely divided colloidal particles, thus giving rise to dense sub-soil horizons.

(d) *Degradation*. Degradation, also called solodisation, occurs on the decomposition of the absorption complex of the soil as a consequence of prolonged leaching of soils that have relatively high absorbed sodium to calcium.

### METHODS OF RECLAMATION

1. If the soil is still in the first phase of evolution (soda szik or solonchak), i.e., if it is simply a saline soil with no alkalization of the absorbing complex, the reclamation will consist merely in washing out the harmful salts.

2. If the soil is in the second phase of evolution (clay szik or solonetz), i.e., if the soil is not only infiltrated with harmful sodium salts, but the sodium cation has gained a more or less dominant position in the absorbing complex, the reclamation will involve two essential procedures—the washing out of the excess of harmful salts, and the re-exchange of sodium by calcium. When the soil salts are neutral this exchange can be effected by chalk. When the reaction is over pH 8, chalk will be ineffective, and gypsum, free sulphuric or hydrochloric acids, or their aluminium and iron salts should be used. (Theoretically, the use of nitric acid should have the same effect, and as these soils are usually poor in available nitrogen, a double effect would be obtained. It is doubtful, however, whether its use would be economically justifiable).

3. In the third phase of alkali soil evolution, i.e., when we have an almost leached alkali soil with not more than 0.15 per cent. total salts and pH 8 or less, chalk and organic manure may be successfully used. But if there are any areas of higher alkalinity it is safer to use gypsum or one of the other materials having a similar effect.

4. With degraded alkali soils, chalk and organic manure will give the most economical results.

As mentioned above, soils in the first stage of alkalization can be reclaimed by mere leaching. The salt content of the irrigation water is important in connection with the reclamation of such soils as was pointed out by Schofield and Headley and by Kelly and Brown.

The experiments of Gedroiz, de Dominicis, Cummins and Kelly and others, showing that extremely adverse chemical and physical conditions develop in sodium saline soils upon leaching out the soluble salts, were all conducted with the aid of distilled water. On the other hand, irrigation waters usually contain more or less dissolved salts.

When an alkali soil is leached with water of this kind much less hydrolysis takes place than with distilled water ; the Ca ions and Mg ions in the water tend to replace sodium from the exchange complex, and the electrolytes flocculate the soil colloids. The net result is that the soil tends to remain in a flocculated condition.

The effectiveness of irrigation water in the reclamation process is



Fig. 16. A rice plantation in which the rice crop is used in the reclamation of saline soils as practised in many parts of Egypt.

dependent both on its total content of soluble salts and on the ratio of its bivalent to monovalent bases. The irrigation water used in California (U.S.A.) contains about 250 p.p.m. total salts with a ratio of sodium to bivalent bases of approximately 1 : 3. Many other irrigation waters are still more favourable, since they contain considerably higher concentrations of calcium and magnesium salts.

Nile water is also regarded as a suitable irrigation water ; except during the period of low stage in June and July, the calcium is always in excess of the sodium, and even during that period, the water must still be regarded as being, on the whole, good for irrigation purposes since the sodium is never greatly in excess of the calcium.

Observations extending over some years on the soils of Gezira (Sudan) showed that with normal use of irrigation-water, subsoil salts did not rise into the root-zone and there impede growth ; they seemed, on the contrary, to be slightly depressed. Sulphates applied in solid form at the soil surface are washed into the subsoil, and this appears to apply also to the salts contained in the irrigation water.

**The Role of Calcium Carbonate in the Leaching of a Sodium Saline Soil.** The role of  $\text{CaCO}_3$  in this respect rests essentially on two principles : (1) The replacing power of Ca ions is considerably greater than that of Na ions. Workers on base exchange generally accept this as a fact. As soon as the concentration of soluble sodium is sufficiently reduced by leaching, Ca ions furnished by Calcium carbonate gradually effect the replacement of sodium. (2) H-clay and H-humate, whether formed by hydrolysis or by the action of acids, react actively with calcium carbonate. The result is the replacement of H ions by Ca ions and the consequent augmentation of replaceable calcium. Generally speaking, it is well agreed that this is the most important reaction that takes place when acid soils are limed.

From the foregoing discussion it is evident that any agency which will bring about an increase in the solubility of the calcium minerals of the soil will promote the reclamation of a sodium saline soil. This is true because the rate of replacement of sodium by calcium is roughly proportional to the concentration of the Ca ions in the soil solution. It is largely for this reason that decaying organic matter and the generation of  $\text{CO}_2$  in the soil by micro-organisms and by plant roots exert a favourable influence on the reclamation process. Consequently, the growth of alkali resistant crops as green manures may be utilized as a practical means of promoting the reclamation process.

Soils in the second stage of alkalization and especially the heavy ones, should first be washed out until a further metamorphosis of the soil becomes possible. It has been stated by de Sigmond that the leaching treatment, as practised in the U.S.A. and Egypt, has not so far succeeded on Hungarian soils, as they have proved to be too impermeable for a thorough washing out. Possibly some chemical treatment might improve the permeability.

Preliminary field experiments showed that by treatment with aluminium sulphate, sulphuric acid, calcium sulphate and similar chemicals, the alkalinity of certain Hungarian soils can be reduced, the coagulation of the soil colloids becomes satisfactory and the

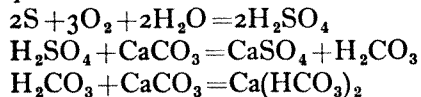
permeability of the soil is restored. Calcium carbonate on the other hand, has no beneficial effect.

Interesting results have been obtained by Dymond and his colleagues in England in the reclamation of soil spoilt by sea water. They observed that flooding of land by sea water at first kills the vegetation by the direct action of the salt. When the flood subsided and the rains started, the soils were washed, resulting in a partial removal of the salts deposited from the sea water. At this stage, the soil was well suited for a good crop yield. But when the soil was further washed by rain, it deteriorated, as the small amounts of salts necessary for the flocculation of the clay particles were removed and the clayey soils did not subside for weeks, and hence cultivation was difficult. Dymond showed that the calcium and magnesium of the soil were displaced by sodium from the salt water. The initial favourable effect was due to the coagulating action of the residual salt, left on the clay. But when the salts were further washed away by rain, the absence of electrolytes caused the soil to be muddy, and flocculation of the clay particles difficult.

Dutch investigators, notably Hissink and his collaborators, from their experience in the Zuider Zee reclamation scheme, are in agreement with the observations of Dymond and his colleagues. Hissink has stated that the soil left after the sea water has drained away is infertile because it contains sodium clay and in order to make it fertile it must be converted into a calcium clay.

A great variety of substances other than chemicals, have been used in the reclamation of alkali soils. In America various kinds of sulphur were used for the reclamation of black alkali soils. It was found that they all gave similar results and differed only in the speed of action, which depends on particle size. Good drainage and a reserve of calcium were found to be necessary for the effective action of sulphur.

**The Theoretical Reactions, which are expected to take place upon applying Sulphur.** As is well known, sulphur undergoes biological oxidation in soil which leads to the formation of sulphuric acid. The acid thus formed reacts with calcium carbonate. The following equations illustrate these reactions :—



Therefore, sulphur, upon oxidation converts calcium carbonate into calcium sulphate and calcium bicarbonate  $\text{Ca}(\text{HCO}_3)_2$ . The calcium

thus made soluble functions in the replacement of sodium from the exchange complex. Or, it is possible that sulphuric acid reacts with Na-clay and Na-humate, converting the same into H-clay and H-humate and sodium sulphate, and that H-clay and H-humate then react with calcium carbonate.

Obviously the sulphur oxidation product (sulphuric acid) and gypsum also converted sodium carbonate, originally present in the soil, into sodium sulphate.

**The Use of Molasses in reclaiming Alkaline Soils.** Alkaline soils of the dry tracts of Northern India and Mysore have been successfully reclaimed by molasses at the rate of one ton per acre and good crops have been grown in these reclaimed areas where no vegetation ever grew.

It is well known that molasses contain between 60 to 70 per cent. of carbohydrates, 4 to 5 per cent. potash, 2 per cent. lime, 0.5 per cent. phosphoric acid, 0.5 per cent. iron and aluminium oxides and 0.5 per cent. combined nitrogen and the rest water. Moreover, molasses are distinctly acidic. Research work carried on in Allahabad, Bangalore, Java, Hawaii, and other sugar-producing countries shows that when molasses is added to the soil, in addition to carbonic acid, organic acids, like acetic, propionic, butyric, lactic, etc., are produced in the early stages in the decomposition and partial oxidation of the carbohydrates present in molasses. Consequently the acids present in molasses and those obtained from the decomposition and partial oxidation can neutralize the alkali of the soils rich in alkali. Moreover, the carbonic acid, which is produced in large amounts from the decomposition and oxidation of the carbohydrates can convert the sodium carbonate into bicarbonate. Also, in the process of the escape of carbonic acid from the molassed soil, the latter is rendered porous and its tilth is improved. Investigations at Allahabad showed definitely that the moisture content of the molassed soil is appreciably higher than that of the unmolassed one. The lime, which is added to the soil along with the molasses, is rendered soluble by the organic acids, formed from molasses and is helpful in the conversion of the sodium soil into the calcium one.

Moreover, alkali soils are very deficient in micro-organisms due to the high pH values and the addition of molasses causes a great increase of activity and growth of micro-organisms.

The oxidation of the energy rich compounds present in the molasses added to the soil liberates energy which is utilized in the fixation

of atmospheric nitrogen. It was shown at Allahabad (India) that the nitrogen content of the alkali soils varying from 0.008 to 0.0025 per cent. increased to 0.05 per cent. on the application of molasses.

**The use of Saltbush in the Reclamation of Alkaline Soils.**

Saltbush was used in the reclamation of alkaline soils in Sudan. Analyses of this plant have been made and showed that although these plants remove much sodium from the soil they can hardly be regarded as a practicable agent in soil improvement, since the amount of sodium in the soil is comparatively large. On the other hand, it appears that by including saltbush in rotation and by removing the crop from the land it is possible to guarantee that no progressive deterioration will occur in consequence of accumulation of sodium introduced in the irrigation water.

More sodium and less potassium are taken out by the better growing saltbush. This tendency is of obvious importance since the supply of potassium in the soil must be conserved.

**Electrodialysis of Alkaline Soils.** The application of electro-dialysis on a field scale is a novel method which holds vast possibilities. Not only are no extraneous chemicals required, but the by-product is sodium hydroxide, which is of economic value. A very important feature of the process is the increased rate of percolation and opening up of the soil. The rate of percolation increases as soon as the electric current is switched on and continues long after it is switched off. This residual effect is of great importance and the one likely to prove most useful in reducing the cost of reclamation.

It was argued that the soil would act as an infinite conductor, and the whole of the electrical energy would be diffused. Practical trials, however, proved this supposition to be incorrect. The method, it seems, holds out promise of practical importance in other directions as well. During the process of electro-reclamation, phosphates and nitrates are likely to move to the upper surface where they will prove useful to plants. This point and the effect on the micro-biological population of the soil are being studied. The application of gypsum together with electric treatment is likely to prove more beneficial than without such treatment. A preliminary experiment in this direction showed a marked decrease in electrical resistance when gypsum was applied.

**The Practical Aspect of the Problem.** The problem of alkaline and saline soils is of the greatest importance for irrigated agriculture. Irrigation is usually practised in valleys, and, unless

special measures are taken to ensure drainage, the ground-water level rises, bringing sodium salts within the effective capillary range of the surface horizons. This leads in time to the replacement of calcium by sodium in the absorbing complex, and, as mentioned before, and in addition, may involve such an increase in salt concentration in the soil moisture as to inhibit plant growth. By the leaching action of irrigation water, saline soil may become changed into an alkaline soil with deflocculation and increase in alkalinity.

In many irrigated areas there are considerable tracts which have gone completely out of cultivation through alkalinization. In some cases the salinization may result from the irrigation water itself having excess of sodium over calcium ions, as is so frequently the case in S. Africa. The soil becomes changed from the calcium to the sodium soil with consequent deterioration in fertility.

In Egypt, the investigations into soil conditions originate in the almost universal replacement of the basin system of irrigation by very largely, free flow perennial irrigation. From the point of view of the soil itself, it has frequently been pointed out that the essential feature distinguishing basin from perennial irrigation is drainage. Good drainage, i.e. aeration of the soil and the prevention of salt accumulation, is ensured under basin irrigation by the annual connection made with the underground water table when the basin is flooded. In land perennially irrigated natural drainage may or may not be good and artificial drainage, apart in some cases from the main drains, which scarcely anyone uses, does not exist. Deterioration of land under perennial irrigation can always be associated with the existence of a high water table which has persisted over a variable period of time. From a historical point of view the immediate adverse effect on crops of a high water table was clearly recognized in Egypt before the last war.

In the Sudan, too, sulphates of sodium and calcium are present in the Gezira soils and although the irrigation water is of good quality it brings appreciable amounts of sodium salts on the land. None, or practically none, of this introduced material is washed from the soil by drainage and, presumably, the continued introduction of sodium salts will, in the course of time, injure the soil and hinder crop growth unless something is done to check or reverse the process.

*Because of these facts, certain authorities have felt that the permanence of irrigated agriculture is doubtful.* However, the knowledge that has been gained through recent investigations shows quite clearly

that irrigated soils need not necessarily be short-lived. In fact, there is a good reason for the belief that, if the drainage conditions are kept favourably, the maintenance of crop production on irrigated soil depends on essentially the same principles, and can be fully as permanent as on non-irrigated soils in humid climates.

We might conclude by saying that, whilst it is known that derelict alkali lands can be reclaimed by reconstituting the calcium soil, comparatively little has been done, in practice, to check deterioration in irrigated soils. The reclamation of such lands and the prevention of deterioration in land now under irrigated cultivation forms one of the most important tasks of soil chemistry.

## CHAPTER 14

# *The Artificial Treatment of Soil and its Chemical Effects*

### PARTIAL STERILIZATION OF SOILS

It has been known for many centuries that heating the soil results in an increase in fertility. Chemical disinfectants have more recently been shown to produce similar results. The general effect is similar to that of adding a nitrogenous fertilizer. Russell and Hutchinson explained this phenomenon by showing that partial sterilization destroys the protozoa which normally keep down the numbers of bacteria so that after the process the formation of nitrates by bacterial action is much more rapid. A further explanation due to Waksman and Starkey is that in untreated soil much of the protein is decomposed by fungal action ; the fungi take up a considerable proportion of the carbon and nitrogen. Partial sterilization destroys the fungi and after the process protein decomposition is for a time entirely due to bacteria ; these latter organisms assimilate much less nitrogen (and carbon) so that more is available for nitrate formation. It has also been demonstrated that heating brings about considerable protein decomposition and also produces some substance which greatly stimulates root growth.

It has been generally recognized that the more favourable the initial biotic condition of the soil to plant development, the greater is the increase in subsequent productivity following treatment. Moreover, virtually all the workers have reported that an increase in yield could be expected wherever disease organisms were controlled by treatment.

**Methods of the Partial Sterilization of Soils.** Soil sterilization, or more correctly "partial soil sterilization" is performed by (1) heat or (2) by treatment with certain chemical agents. Heating of the soil is achieved (a) by baking in an oven, (b) by diffusion of steam

from perforated pipes buried in the soil, or (c) by the passage of an electric current.

### (1) Heat Sterilization

(a) *Baking Sterilization*.—The earliest method employed was that of “baking” over an open fire, and while this was effective in ridding the soil of disease and pests generally, the temperature of the soil was raised so high as to make the soil useless for a considerable time and it was necessary for the soil to be stacked aside to “recover” before it could be used. Since those early efforts at soil sterilization, many other methods have been adopted, but in all cases there has remained the difficulty of adequate and accurate temperature control.

(b) *Steam Sterilization*.—In the case of steam sterilizers, the apparatus is bulky and costly and the layout involved in operating considerable. The steam type of sterilizer is either (1) low pressure, or (2) high pressure. In the low-pressure steam apparatus, it is impossible to raise the temperature of a large amount of soil to 180-200° Fahr. in less than 60 mins. and to attain even near this temperature in the time stated, the apparatus must be exceptionally good.

In the low-pressure apparatus, it is necessary to expose a large area of the soil to the steam to enable the steam to penetrate, and this makes it necessary for the apparatus to be of appreciable dimensions. It is essential that the soil should be removed immediately 180° Fahr. is reached. The high-pressure steam sterilizer is the better of the two steam methods, but here again the apparatus is bulky.

One of the greatest problems in the cultivation of plants in steam sterilized soil is their tendency to grow very fast, and to produce stem and leaf growth at the expense of the fruit. Soil becomes richer in available nitrogen after steaming, and this was considered to be the chief cause of the luxuriant growth, but more recent studies suggest that the remarkable increase in the rate and extent of root development which occurs in steamed soil, may be the cause. Restrictions of root-growth in pots or some other container will correct the growth very easily. The aspect of steam sterilization which presents most problems is that of engineering. More efficient steam boilers, using cheaper fuels and labour-saving devices, would reduce these costs considerably. Research on such problems is badly needed, for steam sterilization is the most effective of all measures for increasing crop production. Cheaper methods would enable it to be used for crops in the open to great advantage. Little research has been done

on the effect of steam sterilization on the soil itself since Sir John Russell and his colleagues first studied the problem 30 years ago. More research is essential in order to ensure substantial progress in the future.

(c) *Electrical sterilization.*—During the last few years, attention has been paid to the application of electricity to soil sterilization. Experience has shown that all harmful pests are exterminated if the temperature of the soil is raised to approximately 200° Fahr. and, furthermore, the useful nitrifying bacteria are not seriously affected unless the temperature is raised to well above this figure.

Two distinctly different types of electric methods have been employed, the first being a box type of container surrounded with suitable heating elements, and the second an electrode type employing electrodes where the current passes through the soil.

In the electrode type sterilizer the soil has to be damped to give it conductivity and so allow sufficiently high currents to pass through, thereby generating heat and raising the soil temperature. The moisture ensures quicker and more even distribution of heat. The passage of an electric current through the soil ensures uniform heating, and with soil of a clayey nature, this is important. The amount of moisture to be added varies with different soils, but this can be very quickly ascertained when an electric sterilizer is first put into use.

The sterilizers, however, are so constructed that they may be used on a potting bench, or they may be mounted on a barrow, thus allowing for filling at one point and transference to some other point where there is a convenient source of electrical supply for the actual process of sterilization. As a general rule, consumption of electricity works out at from 1¼ to 1½ units per cu. ft. of soil treated.

## (2) Chemical Sterilization

Chemical sterilization requires saturation of every part of the soil with a sterilizing agent. This should destroy animal and insect pests and organisms capable of invading plant roots, and restore soil fertility. It should have (1) high penetrative powers, (2) should persist sufficiently long in the soil to do its work, and (3) should then disappear rapidly.

Chemical sterilizers are more selective in action and lack the ease of penetration of steam. Formaldehyde is the best chemical sterilizer. It restores soil fertility, although to a lesser degree than steam, and

destroys fungi and bacteria. It is not effective against soil animals and insects. Sterilizers of the cresylic acid type are more effective against soil animals and insects, but are not so effective against fungi. They do not restore fertility to the same degree as formaldehyde and do not penetrate the soil so well. Various substances are used as specifics for certain pests, e.g. carbon disulphide and mercuric chloride against symphillids, carbon disulphide against wireworms, and chloropicrin against tomato root eelworm.

In Great Britain, large quantities of chemical agents are used annually, partly because they are easier to apply and partly because the supply of steam boilers is not equal to the demand. The chief disadvantages of chemical sterilization are the difficulty of saturating every part of the soil, the difficulty of discovering one substance which will destroy all animal pests and fungus diseases and will also increase fertility, and the length of time which must elapse between soil treatment and planting. It is possible to introduce steam and the vapour of a disinfectant into the soil at the same time. In America formaldehyde has been applied in this way.

#### EFFECT OF PARTIAL STERILIZATION ON SOILS

When soil is partially sterilized by heat soluble nitrogenous compounds, especially ammonia, are formed, often in sufficient quantity to retard seed germination and seedling growth. This consequence of soil sterilization was observed by Pickering, Russell, and Hutchinson in their classical experiments at Woburn and Rothamsted, 1908-1914, experiments which laid the foundation for the use of steam sterilization as a cure for soil sickness in glasshouse borders used for growing tomatoes and cucumbers. Steam sterilization never became popular among growers who raised a variety of plants from seed and failures were the rule rather than the exception. The reason and the remedy were discovered as the result of a large-scale failure following the use of sterilized soil at the John Innes Horticultural Institution in 1934. Experiments showed that plants differed greatly in their tolerance of "excess" ammonia, and it so happened that tomatoes and most of the other plants used by the earlier research workers were relatively tolerant. Further, the general conditions of culture in glasshouse borders are such as to render it unlikely that the excess ammonia would be a disadvantage, indeed it was usually of considerable benefit. The investigations at the John Innes Institution showed that if superphosphate was added to soil

which has been sterilized most of the excess ammonia was temporarily fixed, possibly as a calcium ammonium phosphate. An improved technique of high-pressure steam sterilization was also evolved, and this and the use of superphosphate now enable the grower to sow seeds of all kinds of plants in sterilized soil at once instead of waiting some weeks for the soil to "recover". The new methods are now in wide use and assist the grower to secure all the benefit of soil sterilization (the elimination of weeds, pests and diseases, and the enriching of the soil) without any of the previous disadvantages.

Relatively mild treatments of the soil cause a fall in numbers of bacteria, but when the conditions are again made suitable, the numbers rise considerably. They do not remain high, but sooner or later fall to the normal range of values. More drastic treatments also cause a fall and subsequent rise in bacterial numbers when favourable conditions are restored, but the high numbers are maintained much longer. The phenomena are not confined to soil but are shown also by other complex microbial associations, such as sewage beds. According to Waksman and Starkey the fungi in soil are first much depressed, but increase greatly in numbers soon after the conditions again become favourable. The actinomycetes are also at first depressed, though nothing like as much as the fungi. They do not recover as quickly as the bacteria though they multiply rapidly if cellulose or other energy material be added.

Russell and Hutchinson connected the increased ammonia production with the increased numbers of bacteria, supposing that the new bacterial flora was not widely different from the old, and might therefore be expected to behave like the old, except that, being more numerous, it would accomplish more decomposition. The close relationships between bacterial numbers and ammonia (or nitrate) production in their experiments supported this view. Stormer suggested that the additional ammonia and nitrate came from the decomposition by bacteria of the organisms killed by the partial sterilization process. The amounts formed, however, are much larger than correspond with Russell's estimates of the soil population; in the Rothamsted soil they are of the order of 20 to 50 parts of nitrogen per million of soil, while the whole protozoa and bacterial population represents only 4 parts: estimates of the nitrogen in soil fungi are, however, only rough.

The phenomena are complicated by the circumstance that partial sterilization, however it is done, affects the colloids and the organic

matter of the soil. The effect of heat has been much studied ; it is shown to bring about considerable decomposition of the organic matter, and thus to go some way towards the production of ammonia and nitrate. S. U. Pickering showed that antiseptics had the same kind of effects but to a less degree. All these factors affect the relations between the increased numbers of bacteria and the increased production of ammonia and nitrate in partially sterilized soils.

Heating the soil has been practised from time immemorial in India ; the process is called " rab ", and is mentioned in the Vedas ; the burning of stubble was known by the Romans to increase the fertility of the soil, and various possible explanations were shrewdly put forward by Virgil. Exposure of the soil to the baking heat of the sun is an ancient practice still common in India and in Egypt, where it is known as sheraqi, and has been studied by J. A. Prescott and shown to be due partly to micro-biological, and partly to physical, causes. Lebediantzev considers that this repeated drying and heating of the soil plays no small part in maintaining its fertility in hot countries. The effect on the plant are in all cases described as resembling those of nitrogenous manure.

#### EFFECT OF DRYING AND HEATING SOILS

When a soil is dried or warmed, particularly when it is dried and warmed at the same time, as in summer, various changes occur which cannot yet be satisfactorily explained, nor is the relative importance of temperature and of drying yet known.

The following are the major changes usually observed :—

(1) The solubility of the phosphoric acid, inorganic electrolytes and organic matter is increased both on drying the soil at room temperature and on heating a damp soil. This change is reversed if the soil is left cool and damp for sufficiently long ; the solubility of the phosphoric acid and inorganic salts falls to the level of the undried soil ; that of the organic matter, however, always remains somewhat higher.

(2) The nitrate content tends to decrease on drying or heating but the ammonia content increases.

The magnitude of these effects depends on the soil type ; for instance, in the Russian work it was larger for chernozems than for podzols.

(3) The clay properties of the soil become less pronounced ; the clay particles cement themselves together and act as silt or fine sand

particles. Thus the soil of the Gezira (Sudan) is a very heavy clay which could not be cultivated in England, yet in this hot dry climate it readily crumbles as if it were a loam so long as no water is added.

(4) The quantities of exchangeable bases and of exchangeable hydrogen in a soil seem to change with the changing temperature or dryness ; this was shown by Vinokurov for field soils under different cultivations throughout two years, and by J. L. Steenkamp at Oxford, for soils dried at the ordinary laboratory temperature. H. G. Coles and Morison showed that the acidity of all mineral soils increased considerably on prolonged heating at 98°, followed by a slight decrease on further heating. The changes were reversible. Peats showed slow changes, but not until all the water had been removed, and the changes were irreversible. The change of acidity on drying a soil in air at ordinary laboratory temperature is only small.

Drying or heating a soil thus increases its productivity : and long storage of a dry soil gives still further increases. Gedroiz's experiments with oats grown in soils kept for a number of years are given in Table 22.

TABLE 22

*Effect of Storage in a Dry State on the Productiveness of Soils. Oats, Grams per Pot. (Gedroiz).*

Number of years of Storage	No Manure	Complete Manure	Without Nitrogen	Without Phosphate
0	10.3	83.5	13.5	11
1	17.8	83.5	32.0	19
3	24.6	90.9	23.6	35.4
5	25.0	102.8	32.3	42

In Central Asia, by drying soil in the sun, the temperature of the surface layers rises to 60-65°C. which is sufficient to bring about significant changes in the physico-chemical properties of soils. In Malay rubber plantations, light burning or scorch is recommended as conserving organic material (with consequent prevention of erosion and increase of humus), reducing the chance of soil injury through burning, reducing the loss of the more volatile mineral plant foods and avoiding the uneven distribution in the soil of the large amount of minerals in the ash of burned trees.

Thus the effect of drying the soil is not entirely physical, since important biochemical changes take place during the process. Prescott

has taken account of these changes in his studies of the drying of Egyptian soils, as also has Lebediantzev in studying Russian soils.

**Bare Fallowing.** The practice of leaving land uncropped for a season is very long established. To a large extent the facilities for cleaning the land justify the practice, but over and above that there is an evident tendency for a bare fallow to bring about some improvement in the succeeding crop. The reasons for this improvement may not yet be fully understood, but it is known that the enhanced production of easily available nitrogen compounds in uncropped land is one important factor.

**Addition of Organic Matter.** Organic matter is added to soils in a variety of ways : green manuring (the ploughing in of a crop), application of farmyard manure and so forth. The consequent addition of humus to the soil has important effects on the soil texture, and fertility is further affected by the stimulus given to the important micro-organic population of the soil. When leguminous crops such as tares and vetches are ploughed in, there is the further advantage of enriching the soil in nitrogen.

### DRAINAGE

Waterlogging of the soil has two disadvantages. It cuts off the air supply to the plant roots and therefore prevents the growth of many plants, including some of the most valuable arable crops, grasses and clovers, while allowing docks, thistles, bent grass, buttercups and other weeds to flourish. Waterlogging also leads to reduc-

TABLE 23

*Shows the average composition of suspended matter from lysimeter drainage (1934-1937) at the Macaulay Institute for Soil Research.*

*Filtered through Membrane Filter.*

Constituents	Dried at 105°C.	
	Unmanured	Manured
Loss on Ignition ... ..	12.39	16.58
Silica (SiO <sub>2</sub> ) ... ..	41.37	39.75
Alumina (Al <sub>2</sub> O <sub>3</sub> ) ... ..	23.27	21.27
Ferric Oxide (Fe <sub>2</sub> O <sub>3</sub> ) ... ..	15.72	13.79
Phosphoric Acid (P <sub>2</sub> O <sub>5</sub> ) ... ..	2.62	2.66
Lime (CaO) ... ..	0.44	0.73
Magnesia (MgO) ... ..	1.84	2.03
Potash (K <sub>2</sub> O) ... ..	0.87	2.15
Undetermined (by difference) ... ..	1.18	0.34
	100.00	100.00

tion of nitrates and other oxidised substances with formation of compounds harmful to plant growth. Ferric compounds are reduced to ferrous, manganic to manganous, sulphates to sulphides, etc. The difference in the iron compounds is seen by the change in colour, greenish or bluish being associated with the ferrous state and red or brown with the ferric.

Bad drainage is one of the common causes of infertility on heavy soil of humid countries and on all irrigated soils of arid countries.

The suspended material in drainage waters from lysimeters (table 23) consists largely of compound silicates of iron and aluminium, with smaller amounts of phosphate, calcium, magnesium and potash. The suspended material present in the drainage waters from the manured lysimeter contains on the average more  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Fe}_2\text{O}_3$  than that from the unmanured lysimeter, a little less  $\text{P}_2\text{O}_5$ , and much less  $\text{K}_2\text{O}$  and  $\text{CaO}$ . Organic matter and combined water is much less in the material from the manured lysimeter than from the unmanured one.

#### RESIDUAL EFFECT OF FERTILIZER MATERIALS ON SOILS

**Residual Effect of Nitrogenous Fertilizers.** That certain fertilizer materials exercise an influence upon soil reaction has been recognized for many years. Thus, basic slag was employed as an agricultural liming material in 1881, and it is probable that such use even preceded recognition of the value of the slag as a phosphatic fertilizer material. Again, the ability of commercial calcium cyanamide to neutralize soil acidity has been known from the time of its introduction into the fertilizer trade. These materials, however, are alkaline in character and exhibit their alkalinity to such an extent that basic slag is not used as a source of phosphorus in the preparation of mixed fertilizers, since it would cause the liberation of ammonia from ammonium sulphate and other ammoniacal nitrogenous materials, while calcium cyanamide is used only in limited quantities as a source of nitrogen, since greater quantities would cause reversion of the phosphoric acid of superphosphate to unavailable forms. That such materials should be effective in reducing soil acidity is to be expected.

It has been found that other materials, such as ammonium sulphate and sodium nitrate, which chemically are neutral salts and themselves exhibit no marked alkaline or acid character, also have an ultimate effect upon soil reaction. Since this is not shown immedi-

ately upon application to the soil but develops during the course of the utilization of the nutrient elements by the crops, it is termed "residual effect". It has been explained as caused by a preferential intake by the plants of certain elements over others. Thus, in the case of sodium nitrate the nitrogen as the acidic nitrate is utilized to a greater extent than the basic sodium ion, which is left to neutralize other acidic ions organically in the soil, so that the ultimate residual effect is a decreased acidity or increased alkalinity of the soil.

In the case of fertilizer materials the nitrogen of which undergoes nitrification, an additional factor is the conversion of this nitrogen into the acidic nitrate ion, which as it is formed neutralizes bases in the soil. Thus, in the case of ammonium sulphate, the basic ammonium ions are converted into acidic nitrate ions, and both these and the residual acidic sulphate ion neutralize bases so that the residual effect is an increased acidity or decreased alkalinity of the soil.

**Residual Effect of Potash Fertilizers.** The potash salts customarily used for fertilizer purposes have been found not to affect soil reaction materially, though wood ashes and potassium nitrate, neither of which finds extensive employment as a fertilizer material, cause a decrease in soil acidity. The results of long-continued plot tests have shown that superphosphate has no appreciable effect on soil reaction.

On the basis of the experimental results obtained when various fertilizer materials were employed in vegetation tests, W. H. Pierre drew the conclusion that the differences in the effects of fertilizers on soil reaction are due to differences in their acid-base balance, in that materials containing an excess of a basic element (potassium, sodium, calcium, or magnesium) over the acidic elements (nitrogen, phosphorus, sulphur, and chlorine) give rise to a reduction in soil acidity, whereas materials that have an excess of acidic over basic elements bring about increased soil acidity.

**Residual Effect of Boron Fertilizers.** As only very small amounts are essential to plants, boron in excess, and sometimes in very small excess, may prove toxic. An important question is therefore whether there is any risk of boron accumulating in the soil from continued application. Experiments have shown a strong residual effect of boron in the second year after application. From the results of experiments by Krugel, Dreyspring and Lotthammer on leaching of boron from soils, it was concluded that as about 75 per cent. of the borax left in the soil is likely to be leached out a harmful accumu-

lation of boron is not to be feared. Adding superphosphate to the soil did not increase the loss of boron in the drainage. About 78 per cent. of the boron in the superphosphate-borax mixture was removable by leaching. Two to two and a half years' rainfall are necessary under German conditions for the removal of added boron.

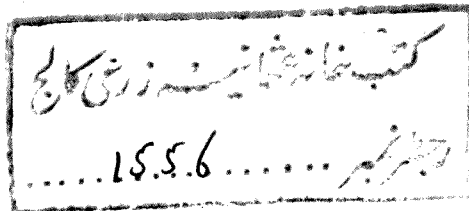
**Residual Effect of Phosphorus Fertilizers.** The availability to plants of the resultant soil phosphates varies greatly with the nature of the soil, but is often so low that the beneficial effects of phosphatic fertilizers are seriously reduced. Efficient utilization of phosphatic fertilizers can therefore be based only on an adequate knowledge of the part played in the phosphate relationships of soils by the diverse reactions collectively referred to as phosphate fixation, the occurrence of which also complicates greatly the interpretation of the results of laboratory determinations of readily soluble phosphate.

In general, experimental work shows that in broadcast applications under ordinary conditions not more than 10 to 20 per cent. of the phosphorus applied is recovered in the first crop. In meadow and pasture crops where the fertilizer is applied on the surface this value is even less.

**Residual Effects of Fertilizers and Manurial Compensation.**

When a tenant leaves a farm in Great Britain he is given credit for all improvements that he has made, including improvement in soil fertility. For many years tables have been in use showing the composition, manurial, and compensation values of various feeding stuffs, and the compensation which should be allowed for fertilizers applied. These tables have recently been revised by a committee representing various agricultural institutions and farmers' organizations. For example, it is estimated that 40 per cent. of the nitrogen, 75 per cent. of the phosphoric acid, and 75 per cent. of the potash contained in a feeding stuff will be found in the manure and that half the value of the manure will remain after one crop has been grown. Another table shows the value of various fertilizers remaining in the soil after the first, second, and third crops are removed. In the case of superphosphate, for example, it is estimated that two-thirds of the value remains after the first crop, one-third after the second crop, and one-sixth after the third crop; whereas in the case of mixed fertilizer it is estimated that one-third of the value remains after the first crop, one-sixth after the second crop, and none after the third crop.

Such a system tends to encourage the tenant farmer to maintain the productivity of the soil.



## CHAPTER 15

### *Chemical Analysis of Soil and its Significance*

ONE of the pressing industrial problems which beset soil chemists is the determination of what fertilizers are likely to be most useful and in what quantities they should be applied to any given soil area.

In the absence of clear conceptions of the nature of plant nutrition and of the constitution of the soil, it is not surprising that soil analysis failed to achieve the practical success expected by its first exponents. Even with the fuller knowledge now at our disposal, it must be admitted that most of the applications of soil analysis to practical ends are of an empirical character. Such, for example, are the methods for determining available plant nutrients by means of extraction with dilute acid solvents.

In considering methods of soil analysis, we may distinguish between absolute and conventional methods. In an absolute method, a determination is made of the total amount of a given constituent present in the soil, or of the amount falling in a definite category of the soil. The determination of the total nitrogen content of the soil is an absolute determination, as is also the determination of the ammoniacal nitrogen content. Similarly we may characterize the determinations of exchangeable bases as absolute determinations. Wherever it is possible to distinguish categories of constituents in the soil, the natural corollary is an absolute method of determination.

On the other hand, we have conventional methods. These are generally the outcome of practical requirements and are of slight significance apart from their practical utility. In the determination of available phosphoric acid by the citric acid extraction method, it is necessary to prescribe every detail of working ; for any variation, as, for example, in the ratio of solvent to soil, or in the time of extraction, may lead to different figures being obtained. The phosphoric acid thus determined does not represent any category

of soil phosphorus which can be defined in terms other than those of the method by which it is obtained. Methods such as these can only have a temporary value and must be superseded when fuller knowledge of the constitution of the soil enables us to distinguish and determine the different categories of soil constituents.

From the standpoint of the study of the soil as a pure science, the chief aim of soil analysis is to characterize the material with which it deals. An ideal system of soil analysis should give a complete quantitative description of the soil, which will serve as a basis for comparison and classification. The need for such a system of analysis is abundantly evident when we consider the qualitative terms in which many of the most important groups of soils have been described. The task of soil classification cannot be considered complete until these subjective descriptions have been translated into definite quantitative data. Such data are as important as the physical and chemical data necessary for the description of chemical compounds.

Progress in the establishment of new methods of analysis is necessarily slow since, even when the investigator has decided what he wishes to determine, his methods must be tested on a wide variety of soils. A method may prove perfectly satisfactory for certain groups of soils and be utterly unsuited for others. It is for this reason that advances in methods of soil examination are now being sought by co-operative efforts among workers in different countries.

Because of the complex composition of natural soil and lack of comprehensive analytical methods it has been suggested that a search should be made for a synthetic soil in which some of the soil phenomena could be studied with fewer complicating factors. Some soil chemists suggest that a synthetic soil can be prepared by mixing a sand with 2.5–10 per cent. of a colloid, plus glucose and  $(\text{NH}_4)_2\text{HPO}_4$  with  $\text{CaCO}_3$  added in sufficient amount to neutralize any acids produced.

**Evaluating Fertilizer Needs.** Since the time when Liebig's mineral theory was new, the leading science as regards the determination of the nutritional requirements of plants has always been chemistry. For some three generations chemical methods were confined to establishing the extent of nutrients in the soil ; and then slowly the idea of using mild extractants to gain an approximation to the "available" plant food in fertilizers and in soil took hold.

More recently still, chemical methods have been supplemented by those involving yield responses of young crop plants or of fungi and other micro-organisms, and quite lately the development of particular plants which are not usually regarded as crop plants (for example, the sunflower) has been claimed to have value in indicating the nutrient status of a soil.

**Total Chemical Analysis of the Soil.** The plant nutrient content of a soil is usually divided into two arbitrary groups : the potential supply and the available supply. The potential supply is determined by a total chemical analysis of the soil and tells us very little regarding the fertilizer needs of the soil. The growth of plants is determined by the nature of the chemical changes taking place in the soil and plant, and not by the total or potential plant-nutrient content of the soil. A total chemical analysis of a soil tells us little regarding the rate at which plant nutrients will become available during the growing season, although if good growing conditions prevail, a soil analysing high in plant nutrients would generally be expected to produce more available nutrients during the growing season than a soil low in total plant nutrients. However, a total chemical analysis of soils is of value to the soil chemist and hence serves a useful purpose although it is of little service to the farmer.

According to G. W. Robinson total analysis may find some use in connection with methods for estimating the degree of weathering of soils. However such analyses, involving the determination of silica, sesquioxides, titanium oxide, alkalies, and alkaline earths, represent a very considerable mass of effort, yet the value of information to be derived from them is of an entirely low order of magnitude, since they fail to distinguish between the unweathered minerals and the weathering complex. In Robinson's opinion they may be compared with results of analysis in animal nutrition.

**Rapid Chemical Tests.** "Spot tests" or "rapid chemical methods" have been widely applied in recent years. They are to a large extent empirical, and while the indications they give are objective, the interpretation of the indications is subjective. The successful spot tester has to acquire a special soil sense derived from wide experience that enables him to assess the fertilizer requirements of the soil from the results of the tests by instinct rather than by reference to standard charts or tables. This sense is somewhat similar to that possessed by a very few who can accurately assess the quality of soil by walking over it.

Recently a large number of "quick" tests have been widely used for estimating the amount of each fertilizer element to the acre that is available.

The test used by Morgan may be cited to illustrate the general type of procedure. He uses a mixture of acetic acid and sodium acetate of approximately 0.5 normal acidity which is buffered at a pH of 4.8. The extracting solution is passed through the soil; or the soil is placed in the solution, shaken, and filtered. The filtered solution is the soil extract that is tested for the various fertility elements. In view of the fact that a very small quantity of soil is used, great care is required in sampling in order that the sample may be representative of the soil from which it was taken. Soils are found to be "high," "medium," or "low" in the various constituents, these designations being based on arbitrary standards.

Tests of this nature are subject to limitations under many soil and cropping conditions. Much information in addition to that supplied by the test is needed as a basis for recommending the fertilization that should be given to the soil for a specified crop. Moreover, quite aside from the results of the test, consideration must be given to such factors as those governing the quantity and kind of fertilizer that may be used with profit by the farmer.

The economic value which has resulted from improved soil management through the use of such methods in the hands of reliable workers would be difficult to estimate. Equally important, perhaps, is the role which they have played in causing land-users to become aware of existing and ever occurring soil problems, as well as to be more considerate of the fast disappearance of natural fertility.

In addition to the place merited by rapid soil testing methods in practical agriculture, perhaps use can be made of them in connection with vegetative experiments in the field, plot, or greenhouse. Employment of these tests in conjunction with such studies might yield evidence of a more definite nature regarding the availabilities of one or more nutrients than we could surmise from mere observations of the vegetative development, upon which we have relied in the past to a large extent.

**The Use of the Plant in determining Manurial Requirements.** When it was first realized that the chemical analysis of soils gave results that could not be interpreted in any simple way, some attention was given to the possibility of making use of the

analyses of plants grown in the soils in question. An endeavour was made to ascertain whether the percentage of phosphate and potash in the ash of a plant could be used as a guide to the manurial requirements of the soil in which it had grown. There has been very little development on these lines until quite recently when a method proposed by Neubauer has become extensively used in Germany.

**Neubauer's Seedling Method.** In this method the soil is mixed with pure sand, and rye seedlings are grown for seventeen days from the date of sowing. On the eighteenth day the shoots are removed and the percentage of potash and phosphate in the ash is determined. It is claimed that unless these percentages reach values of the order of 0.025 per cent.  $K_2O$  and 0.006 per cent.  $P_2O_5$ , there is an insufficiency of available potash or phosphate in the soil to produce a maximum crop.

**Mitscherlich's Pot Culture Method.** Another method also extensively used in Germany is based upon the view, which Mitscherlich holds on the basis of evidence of pot experiments, that the amount of any given manurial constituent which is required to produce a maximum crop is independent of the amounts of the other constituents present. For example, if a soil contains adequate amounts of phosphate and nitrogen but is poor in potash, increasing applications of potash will produce increased growth to a certain maximum. If the amounts of phosphate and nitrogen had been inadequate, increasing applications of potash would still have produced increases in crop growth up to a certain maximum. That maximum would be less than when phosphate and nitrogen supplies are adequate, but the amount of potash required to produce it would, according to Mitscherlich, be the same. On this assumption it is possible by pot experiments in which there are four units, one with an adequate supply of potash, phosphate and nitrogen, and three others in which each of these manurial constituents is omitted in turn, to compute the manurial requirements of a soil.

The validity of both the Neubauer and Mitscherlich methods is the subject of very considerable discussion.

***Aspergillus niger* Method.** Another biological method which is coming into use for determining the potassium status of a soil depends upon the growth made by *Aspergillus niger* in a nutrient solution from which potassium is omitted and to which a definite quantity of the soil in question is added. The mycelium

is dependent upon the soil for its potash, and the increase in weight that it makes when incubated under standard conditions gives some guide to the amount of available potassium in the soil. The method may also be used to examine the phosphate status of a soil.

**Sap and Tissue Tests.** Methods involving the testing of the expressed sap of plants and of plant tissues have been developed with the idea of aiding in assessing fertilizer requirements. Obviously, several limitations have presented themselves in these methods. These tests are of value in that they indicate the content of mineral elements in soluble forms in the plant, and before an element can be of direct benefit it must be taken up by the plant. In this respect they are superior to soil tests which do not foretell the amounts of nutrients a plant will absorb. However, tests of the expressed sap of plants do not permit interpretation at seeding time, which is important from the standpoint of determining the immediate fertilizer requirements. The results of these tests may indicate certain limiting elements which may be used as a guide in making fertilizer recommendations the following year on the same crop and perhaps be of value in indicating the kind of fertilizer to apply as a top dressing or side dressing during the current season.

In regard to tests on the sap and tissue of the plant, the matter of determining the part of the plant to test and the stage of maturity of the plant when samples should be taken must be considered. Regardless of the various limitations of these plant tests and also of the rapid soil tests, when the two are used simultaneously they offer much information regarding the chemical condition of the soil and are most valuable guides in making fertilizer recommendations.

The "triple-analysis" method, devised by Lundegardh and widely used for advisory purposes in Sweden, is based on determinations of the N, P and K contents of leaves. These figures are said to give direct indications from the plant's point of view of the ability of soil nutrients. Practical advantages of the triple-analysis method are (1) the ease and cheapness with which it can be carried out ; (2) N requirement is as easily determined as P or K requirement ; (3) it takes full account of the dependence of one nutrient effect on the others. The results are expressed in simple diagrammatic form which shows, for example, that a low content of both P and K in the leaf may mean that neither fertilizer element by itself will have much effect, but that application of either will result in a good response to the other.

**Soil Adsorption Tests.** Purvis and Blume have suggested that instead of determining the amounts of potash and phosphorus removed from the soil by a specific extractant, the quantities absorbed by the soil from a solution of standard strength be determined. They point out that a measure of the amounts absorbed by a soil should be a better criterion of availability than a determination of the amounts present in an arbitrarily defined "available" condition.

**Pot Tests.** Pot tests with many modifications have been used by various investigators. Essentially these tests consist in filling a number of pots with soil material and in adding various fertilizer salts. The need for fertilizer is indicated by the growth of the crop, by amount of dry matter produced, or by analysis of the plant ash. These tests are usually conducted under greenhouse or laboratory conditions and permit the control of moisture supply, temperature, and other factors that cannot be controlled in conducting field tests. Nevertheless, the results have to be interpreted in terms of field conditions if they are to be of value to farmers. This constitutes the chief objection to the method. Regardless of this criticism, pot tests generally are regarded as ranking second to field experiments for determining the fertilizer needs of a soil.

It seems, therefore, that soil tests at their best supply only a part, and often the least important part, of the information that should be considered in making fertility recommendations. The texture and structure of the soil, its organic content, its drainage, its previous lime and fertilizer treatments, the preceding crops and the rotation that is to be followed are a few of the factors most worthy of attention. If this is the situation, the practical importance of chemical tests has been overrated and the public confidence to a certain extent misplaced. It appears clear, however, that no single method will give trustworthy information in all cases, but that there is a number of methods which can give trustworthy results in the majority of cases.

**Field Experiments.** The most reliable method, however, for evaluating fertilizer needs is field experiments. One of the best places to carry on these field experiments is the individual farm. A farmer, for example, can well afford to try fertilizers in an experimental way and to determine for himself if they pay on his particular soils and in his own soil-management system. Each farm is a particular problem in itself.

The solution of individual or community fertility problems is

best accomplished by the aid of experienced and technically trained men, who understand the scientific principles underlying the common field procedures and who are also in touch with the experiences of farmers over wide and diverse areas. These specialists can make the necessary chemical tests or have them made, and correlate them with the other phases that bear on the situation.

**The Thermo-Kinetic Tests of Soil Fertility.** In searching for suitable tests for soil fertility, soil chemists have been aided in recent years by physicists and biologists, but in spite of all efforts the improvement of soils is not yet an operation of which the measures can be prescribed from the results of experiments. There is not even agreement as to what constitutes fertility. To some it denotes the amount of plant nutrients in soil ; others measure it by yield capacity ; and others link it in some unknown manner with the activity of soil micro-organisms in decomposing organic matter. It must be admitted that neither full-scale chemical analysis nor the rapid chemical methods nor any of the numerous biological methods of testing soil offers a satisfactory solution to the problem of the determination of soil fertility. To these have recently been added, by Dr. E. H. Reinau, of Berlin, a new method based on a measurement of soil respiration and which he calls the " thermo-kinetic " test of soil fertility.

**Agrobiology.** In recent years some American workers put forward the principles of a new branch of agricultural science which they gave the name of Agrobiology.

Agrobiology may be described as an arithmetic of plant growth by which crop yields may be expressed in terms of a known degree of soil fertility, and *vice versa*. It can be assumed that all plants have fundamentally identical natures and respond in an identical manner to the same positive external stimulations. For instance, if a certain amount of positive stimulation—water, nitrogen, potash, etc.—is required for the production of half the potential yield of a given crop, these amounts will produce half the potential yield of any other crop grown under identical conditions. By dealing only with the positive factors affecting plant growth, and ignoring negative factors like soil toxicity, climatic changes and plant diseases (with which the practical grower has, unfortunately, to deal) the agrobiologist arrives at the conclusion that agriculture could be enormously more productive than it is.

When yields calculated in this way are compared with the

maximum known yields it is seen that the plant breeders have advanced all but a few of our important crops far towards the calculated limits. Some varieties of maize are stated to have actually given the yields predicted by agrobiolgy, whilst wheat, cotton, rice and sugar cane are not far behind. However, the agrobiologist's figures show that the average crop yields in American farming are still only ten to twenty per cent. of either the known maximum yields or those predicted by agrobiolgy. Willcox believes that such a low level of efficiency in crop production could be met by the adoption of more intensive farming based on agrobiological principles, in which bumper crops would be the rule rather than the exception.

To the agrobiologist, the soil is a container to be filled with as many units of moisture, nitrogen, potash, etc. as the farmer can afford, with the proviso that the final N-P-K ratio is appropriate. The negative factors of plant growth, such as soil toxicity, reversion of fertilizers in the soil, poor soil structure, drainage difficulties, plant diseases and so on, are stated to be none of his concern. In short, it is left to soil chemists, soil physicists and plant pathologists to discover how to bring about field conditions which will fulfil agrobiological requirements.

Such calculations tend to exaggerate rather than to reinforce the claims of agrobiolgy. It is true, however, that phenomenally high crops yields even above the agrobiological limits have been obtained in the field under favourable conditions of location, climate, soil and so on. For instance, at Inverness, British Columbia, the yield of potatoes in a field experiment was 1,735 bushels per acre (*Sci. Agric.* Vol. 11, 1931, pp. 760-774), whereas the maximum yield is 1,550 bushels per acre according to agrobiological theory. To take another example, the average yield of sugar cane in Queensland is about 16 tons per acre, but in one experiment 144 tons of cane was harvested (Thirty-second Annual Report of the Bureau of Sugar Experiment Stations, Queensland, 1932, p. 34). The agrobiological maximum is 192 tons per acre. Willcox gives examples of progress in raising the level of crop production in different parts of the world, notably with wheat, rice and sugar cane, and as he himself admits, such progress shows, quite apart from agrobiolgy, that room still remains for a considerably greater efficiency in the utilization of our soil resources. If agrobiolgy succeeds in getting this fact recognized by the many instead of by the few it will have served a very useful purpose.

*The Mineralogy of Soil Clays*

THE introduction of new methods of research, chiefly of X-ray diffraction analysis, has brought considerable advances in our knowledge of soil colloids within the last 15 years. It has been shown that the bulk of many soil colloids is crystalline and composed of clay minerals often accompanied by oxides or hydroxides of silicon, iron or aluminium. The clay minerals themselves have been studied and their atomic arrangements and properties are now known to some extent.

The clay fraction consists of particles which are, to a great extent, so small that they cannot be distinguished even with the help of the most powerful microscopes, as was revealed in Chapter III. In the last decade great advances have been made in the study of the clay fraction with the aid of X-ray diffraction technique, and more recently by the use of the electron microscope. This uses beams of electrons in vacuum instead of beams of light, and electrostatic and magnetic "lenses" instead of the optical lenses of the ordinary microscope. In this way useful magnifications up to 40,000 diameters have been obtained, as compared with a maximum of about 2,000 diameters with the best optical microscopes. With it the shapes of the smallest particulate constituents of the soil can be made visible, since its practical resolving power has already approached  $2 \mu$  and the theoretical limit has by no means been reached. It is particularly well adapted to the study of the clay minerals; first, in order to characterize them by their appearance, and second, to assess more exactly than has hitherto been possible the contribution of their crystal habit to other physical and chemical properties.

By means of the electron microscope it is possible to gain an insight into the size of the ultimate particles and thus this instrument has opened the way for a more definite understanding of the

effect of particle size upon the properties of clays. Considering the limited use previously made of the electron microscope, it is not unreasonable to expect that with the development of improved techniques and experience this instrument will yield extremely valuable information, not only in regard to the clay minerals but also concerning that fraction of soil which appears by other means of investigation to be amorphous.

By these tools, soil chemists have been able to show that clay consists to a large extent of crystalline minerals of recognizable types, bearing little resemblance to the sand minerals. Thus, instead of being irregular shaped lumps, they are largely plate-like (as is mica), but may also be rods or may consist of tufts of needle-like crystals. They rejoice in such names as montmorillonite, nontronite, bentonite and beidellite.

These minerals are chemically active, some more so than others. They are almost certainly residues of the weathering process; in addition there are non-crystalline constituents of the clay fraction, such as iron hydroxide, which are probably precipitated from the soil solution. Clay which consists largely of such material possesses properties which are different from those consisting mostly of the crystalline minerals. For example, a soil sample from East Africa containing 80 per cent. of clay, but largely of the iron hydroxide type, was reported to be a friable loam, and not a sticky clay. To-day, therefore, from studies involving the four-fold approach which utilizes X-ray diffraction technique, specialized optical methods, thermal methods, and chemical analyses, the structures and composition of the clay minerals have been determined and their relationships clearly demonstrated.

**Structure of the Clay Minerals.** While much valuable data had been collected on the clay minerals before 1930, the greater part of the research had been confined to the kaolin minerals of the china clays, which frequently contain large crystals, of which the optical constants could be determined. The minerals montmorillonite and beidellite had been described, and the existence of certain alkali-bearing clays resembling the micas recognized, but there was still great confusion in nomenclature, and the amorphous nature of many clays, including those of the soil colloids, was still believed in.

The year 1930, however, marked a distinct advance in our knowledge, and it set the stage for the very rapid strides which have been made during the last decade. In that year the crystalline

nature of even the finest clays and soil colloids was firmly established, by Hendricks and Fry (1930), Kelly, Dore and Brown (1931), and Marshall (1930) working quite independently.

Classification of clay minerals necessarily depends upon their crystal structures, but it is perhaps best to direct attention first to changes in their chemical compositions as affected by substitution of one element for another, that is, by isomorphous replacements. Clay minerals can be defined as hydrous aluminium, magnesium or iron silicates of small grain size, containing minor amounts of alkaline earths and possibly other elements (Ti, Cr, Mn, etc.).

At present a considerable amount of work is in progress on the actual lattice structure of clays. According to the ideas of L. Pauling, based on X-ray diffraction studies, it is supposed that the clay minerals have crystal lattices built up of successive layers of linked atoms. The theories advanced for the crystal structure of the clay minerals have certain consequences in connection with the behaviour of the so-called exchangeable cations.

C. E. Marshall has adduced evidence for the crystalline character of clays from a study of their double-refraction properties, and has shown that the univalent and bivalent cations associated with clays are not, as was supposed by some workers, present at the surface alone, but can occupy definite positions within the crystal lattice. From ultra-microscopical observations, he has concluded that, for a given clay, each cationic combination has a characteristic degree of dispersion.

#### IDENTIFICATION OF MINERALS

The tendency at present is to determine as far as possible quantitatively the mineral composition of any given soil colloid and for this purpose the following methods are usually utilized.

- (1) X-Ray methods.
- (2) Thermal methods.
- (3) Optical methods.
- (4) Chemical methods.

(1) **X-Ray methods.** It was not until the application of X-ray diffraction that the essential crystallinity of the colloidal fraction of soils was fully demonstrated, although a few soil chemists had recognized the fact, and possible combinations of the constituents were determined. This development was made possible by the rapid advance in knowledge of the structures and ranges of compo-

sitions of the clay minerals. Applications of methods now available make possible identification of the major inorganic components of soil colloids and semi-quantitative estimation of their amounts. But it must be noted that although much work has been done on the mineralogy of the clays, the nomenclature of some of the groups is still confused and there is doubt about some of the details of crystal structures.

Every crystalline substance gives a characteristic X-ray diffraction pattern, and no two chemically distinct crystalline materials have ever been found which show identical diffraction patterns. Moreover, the composite pattern produced by a mixture of substances consists of the separate patterns superimposed. The relative intensities of the separate patterns depend on the relative quantities of each constituent present. A mixture of crystalline substances may, therefore, be analysed qualitatively and (to a limited extent) quantitatively. The extent of the application of the X-ray method to analysis will be apparent when it is realized how rare is the so-called amorphous state. As a broad generalization we may say that practically all inorganic matter in the solid state is crystalline. Perhaps the most conspicuous exception to this generalization is matter in the glassy state. Perhaps it is more accurate to say that all matter in the solid state shows a more or less highly developed structure. In the organic field it is probable that nearly all naturally-occurring fine particles are crystals. It is surprising to learn that chemical precipitates and colloidal particles come within the category of crystals. They give typical powder diffraction patterns unless the particle size is too small. Sharp continuous lines in the powder diffraction pattern are given when the particle size lies within certain range. Below this range the lines begin to lose their continuity. Measurement of line-breadth provides a means of measuring crystal particle size in the absence of other factors influencing line-breadth.

If crystalline minerals other than the clays are present, their identity can, in some cases at least, be established by reference to the diffraction patterns of known minerals.

While X-ray analysis affords a means of identification of the several classes of minerals present in soil colloids, it does not necessarily yield all the important information about soil colloids. A combination of two or more types of methods is the more instructive.

*Limitations of the X-ray Method.* The X-ray method, however, has its limitations. By this method only groups of clay minerals can be identified with any degree of certainty. Then again, the detection of amorphous material is uncertain. Lastly, although the X-ray method has pushed investigation to much lower limits of size of particles, there still exists a lower limit. Material still finer may be of importance.

(2) **Thermal Methods.** Every group of minerals has a particular dehydration curve. These curves are obtained by heating a certain weight of the unknown mineral to various temperatures and tabulating the loss in weight against temperature. By comparing the dehydration curve of the mineral in question with the known curves of the various groups of minerals, we may be able to identify the group to which that particular mineral belongs.

As we mentioned before, it is possible to determine the types of clay minerals present in soil colloids by comparing the X-ray diffraction patterns with those of known minerals. The determination is especially facilitated by X-raying the samples at widely varying moisture content. The dehydration curves of the different clay minerals show that OH lattice constituents pass off as water vapour at temperatures which are characteristic for each class. The consequence is that their X-ray diffraction pattern is destroyed at these temperatures.

One of the most characteristic X-ray lines of the montmorillonitic clays corresponds to a spacing of about  $15\text{\AA}$ ,<sup>1</sup> in the air-dried form of the clay and of from  $9.5$  to  $10\text{\AA}$  in the material heated to  $5,000^\circ\text{C}$ . The diffraction line characteristic for the identification of the kaolinitic clays corresponds to a spacing of about  $7.0\text{\AA}$ : this spacing is not affected by heat treatment below the temperature of decomposition, but at about  $5,000^\circ\text{C}$ . this, as well as the other lines of these clays, disappears as a result of decomposition. The corresponding line of the "x" mineral is found at about  $10\text{\AA}$ , and remains in this position until the sample is heated above  $5,000^\circ\text{C}$ . By combination of partial dehydration with X-ray analysis, therefore, it is possible to determine what clay mineral is present, whether alone or as mixtures of other types of clays.

(3) **Electron Microscope.** This technique is so new that it has not yet been used much for the identification of minerals in soil colloids, but it will undoubtedly prove to be very useful in the

<sup>1</sup>  $\text{\AA} = 10^{-8}$  cm.

future. It serves to determine size and shape of particles down to 50A or less, and at present most of the work done is concerned with data for standard minerals. An application to soil colloids has been given by Hofmann and by Humbert and Marshall. One of the chief results so far has been the observation that rod-shaped particles of clay minerals are more common than had formerly been assumed.

The electron microscope gives information, however, (which no other method gives) as to the shape of the colloid particles. This has considerable interest apart from its possible use in analysis. Even in analysis the information given by the electron microscope may help in identifying material at present beyond the reach of X-rays.

(4) **Chemical Methods.** The most important chemical method used in the identification of clay minerals—apart from chemical analysis—is base exchange. Clay minerals and zeolites are the chief inorganic crystalline materials which show the phenomenon of base exchange to a marked degree. The total base exchange capacity could be used for mineral identification if it were constant for a given clay mineral and if different minerals showed sufficient variation. Both conditions seem to hold for certain groups of clay minerals, but in spite of much published work our knowledge about base exchange is very incomplete. Grinding increases the apparent base exchange capacity of many silicates, but it probably produces considerable lattice disturbances and alters the chemical properties of the silicates.

## CLASSIFICATION OF CLAY MINERALS

Although there are necessarily still certain doubts in regard to crystal structures, and some confusion in nomenclature, a satisfactory grouping of the clay minerals is now possible. It may be noted, however, that, while crystal structures necessarily form the basis of the classification of the clay minerals, changes in chemical composition, as affected by the substitution of one element for another, are important. Since isomorphous replacement is rather the rule than the exception, it may be a complicating factor in any attempt at classification, especially in the clay minerals for which the sources of origin may vary quite considerably.

The clay minerals can be divided into three general groups.

- (1) Kaolin minerals.
- (2) Montmorillonite minerals.
- (3) Hydrous micas.

To these three groups may be added a fourth, the members of which, while not strictly clay minerals, nevertheless occur in association with them, in greater or smaller amounts, and may become particularly important in soil clays. This group embraces—

- (4) Accessory minerals, including oxides and hydroxides of silicon, alumina, and iron.

(1) **Kaolin Minerals.** In 1931 Ross and Kerr first differentiated the four members of the kaolin group from a study of their optical properties and X-ray patterns, and in the following year Gruner not only confirmed the differentiation, but was able to assign the correct crystal structure to each. He indicated that the differences were due to the way in which the Al and Si sheets were stacked one above the other. The four members of this group are :—

- (a) Kaolinite.
- (b) Halloysite.
- (c) Nacrite.
- (d) Dickite.

Kaolinite and halloysite are difficult to distinguish in soils and clays, and, in the absence of optical and dehydration data, are usually reported simply as kaolinite.

It should be noted that only kaolinite and halloysite have been reported as occurring in soils, nacrite and dickite being of hydrothermal origin. Owing to the small number of ionic replacements in the kaolin lattice the minerals of this group have a very low cation-exchange capacity, which is here due almost entirely to the exposed (OH) ions of the lattice, with those (OH) ions produced through polarization of water molecules by exposed silica and aluminations.

Increases in exchange capacity resultant upon grinding are due to the exposure of further (OH) ions, of the basal (OH) sheet through distortion, and to a lesser extent through an increase in surface area exposure. Phosphate exchange is also important in this mineral type. Chemical and greenhouse experiments showed that soils with a kaolinic type of clay have a high capacity to fix phosphate and a low phosphate availability.

A soil containing a certain amount of clay of kaolin type will probably have a greater permeability, lower shear resistance and less volume changes on alterations of water content, than a soil with the same amount of clay of montmorillonite type.

(2) **Montmorillonite Minerals.** While the mineralogy of the montmorillonite group has not been studied to the same extent as that of the kaolin group, many analyses have been listed by Nagelschmidt (1938), Hofmann and Bilk (1936).

The minerals of this group are characterized by their ability to take up water (represented by  $xH_2O$ ) in the formula, since it is indefinite in amount), reversibly, between the alumino-silicate lattice layers, resulting in very definite swelling properties in the minerals. They are further characterized by their high cation-exchange capacities which are due essentially to the extensive ionic replacements in the lattice, and to a lesser extent to exposed (OH) ions. Calcium ions which are larger than those of magnesium or iron, cannot be accommodated very well within the (Al) layers. In consequence, calcium is usually present in very much smaller amounts, and then only as exchangeable ions, rather than as an essential part of the lattice.

Montmorillonites are seldom free from magnesium, and high proportions are usually present in those of marine origin. Beidellite is usually low in magnesium and high in iron. Montmorillonite is one of the most widespread of the clay minerals. It is the principal constituent of the bentonites.

Minerals of this group have been identified in soils throughout the world. They are characteristic of soils formed on many types of parent material, especially those of a basic nature where reduced moisture conditions prevail, active leaching has practically ceased, and protracted periods of drought occur.

The name "bentonite" is often used as synonymous with "montmorillonite", but more strictly it refers only to material derived from volcanic ash and might sometimes be related to the micas rather than to the montmorillonites; that is, bentonite is a rock rather than a mineral name.

(3) **Hydrous Micaceous Minerals.** In recent years, a third group of clay minerals, related to the micas, has been identified. Although, apart from glauconite, the clay mineral of green-sands, no definite individual species have been recognized, members of the group may be compared with glauconite itself or the illites of Grim and his co-

workers (1937). While showing similarities to the micas in structure and composition they differ principally in their higher water content, and may thus be described as hydrous micas (Hendricks and Alexander, 1939) and this term has been adopted here for their classification.

These minerals were described as "alkali-bearing clays" by Ross and Kerr and were first recognized in soil colloids by Hendricks and Fry in 1930. Many workers have recognized mica-like materials formed as intermediate products during the transformation of feldspar into kaolinite. Denison, Fry and Gile followed the alteration in composition of muscovite and biotite undergoing weathering, and their investigations indicated continuous variations from the true micas through the glauconite and illite stages. Weathering of the micas was shown to be accompanied by an increase in water content and decrease in potassium, as well as an increase in aluminium at the expense of iron and magnesium.

(4) **Accessory Minerals.** The minerals of this group, while not clay minerals in the strict sense of the implied term clay, and in that they have a much wider distribution in other types of deposits and rock formations, are nevertheless widely distributed throughout clay deposits. While definitely deleterious in certain clays, their possible importance, especially in soil colloids, warrants their inclusion and brief mention here. These accessory minerals include the free oxides and free hydrous oxides of iron, aluminium, and silicon.

Free silica is fairly uniformly distributed in both clays and soil colloids, either as crystalline quartz ( $\text{SiO}_2$ ) or B-cristobalite or in the amorphous state.

Of the iron and aluminium minerals, haematite ( $\text{Fe}_2\text{O}_3$ ), magnetite ( $\text{Fe}_3\text{O}_4$ ), goethite ( $\text{HFeO}_2$ ) amorphous limonite ( $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$ ), gibbsite [ $\text{Al}(\text{OH})_3$ ], diaspore ( $\text{HAIO}_2$ ), boehmite [ $\text{AlO}(\text{OH})$ ] and amorphous bauxite ( $\text{Al}_2\text{O}_3 \cdot n\text{H}_2\text{O}$ ) have all been identified in clays and soil colloids. They are more usually associated with the kaolin minerals, since the iron present in micas and other ferro-magnesian minerals is expelled as oxides or hydrous oxides when weathering to kaolin takes place. The montmorillonites and hydrous micas, on the other hand, can retain iron as weathering proceeds. Yellow and red colours of clays and soil colloids, while in part intrinsic to the clays, are due essentially to the presence of these iron minerals.

The logical grouping of the clay minerals has been discussed by Kerr, Hendricks and Alexander, Nagelschmidt, and others.

### FORMATION OF CLAY MINERALS

Many workers have established the fact that each of the three principal types of clay minerals is widely distributed in the soils of various parts of the world. Kaoline, montmorillonite, and mica-like clays have been found in soils of practically all types of climate, and each of them seems to have been formed from various kinds of parent-rocks. Kaolinite occurs in well-leached soils of both the humid temperate and the humid tropical climates.

Clay-mineral formation is undoubtedly a chemical process, and all known chemical processes are influenced, usually markedly, by temperature, pressure, the concentration of soluble electrolytes present, and by pH. It would indeed be singular if clay formation should prove to be an exception. According to C. S. Ross, in the formation of clay minerals, organic matter acts chiefly as a reducing agent and in promoting removal of bases through organic acids.

It is possible that different types of clay minerals are formed in soils at different stages in the weathering process, or, more probably, that the leaching conditions exert an important influence on the kinds of clay minerals, both as regards their formation and occurrence. Noll synthesized kaolinite and montmorillonite recently. He found that when  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$  are heated together under pressure in the presence of  $\text{H}_2\text{O}$ , the temperature, the pH and the concentration of certain bases present determine the kind of mineral that is formed. If Na, K, Ca, Mg, Cs, or Be is present in a certain range of concentration, montmorillonite, which is the chief mineral of the bentonitic clays, is formed. If NaOH is the only base present and in relatively high concentration, analcite is formed, which is a mineral related to the zeolites but is not a clay mineral. On the other hand, if the same mixture of  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$  is heated under pressure in the presence of either pure  $\text{H}_2\text{O}$  or an aqueous solution of HCl, but in the total absence of bases, or when the concentration of bases is very low, kaolinite is formed. These results suggest that the kind and abundance of soluble bases present in the weathering materials and the pH of the medium may exert a significant influence on the type of clay mineral that is formed.

It has been established, however, that acid leaching conditions will lead to kaolin formation, and alkaline illuvial conditions to montmorillonite formation in soil colloids. The conditions for the occurrence of illite are less clear. It has been found as the chief component of arctic-soil colloids and is often found in soils from temperate regions, but almost never in those from the wet tropics. Thus it would seem to be unstable under acid eluvial conditions, and the presence of illite might indicate freshness of the parent material, or low intensity of chemical weathering, or both these factors.

**Potash and Phosphate Fixation.** If potash and phosphorus are added to the soil as fertilizers, only up to one-third is usually recovered in the crop under field conditions, and more than one-half may remain in the soil in a form believed to be unavailable to plants. The effect is known as potash or phosphate fixation, and both are very complex phenomena. It has been suggested that potash fixation may be due to the formation of muscovite in the soil, and phosphate fixation to the formation of crystalline kaolin-phosphate complexes. Both claims appear at present unsubstantiated and the subject requires further work. There may be a series of equilibria for  $K_2O$ : soluble  $\xrightleftharpoons[1]{\leftarrow}$  exchangeable  $\xrightleftharpoons[2]{\rightarrow}$  fixed by montmorillonite  $\xrightleftharpoons[3]{\leftarrow}$  illite  $\xrightleftharpoons[4]{\rightarrow}$  muscovite.

Inorganic phosphate fixation is also believed to be due to the formation of hydroxy-apatite in alkaline, and of basic iron and aluminium phosphates in acid soils, or to absorption phenomena.

**The Mineralogical Composition of the Soil Profile and its significance.** Variations in mineral composition throughout the profile, or within any horizon, with grain size, are important in assessing changes likely to occur in the soil. Thus if in any given sample a clay mineral increases in proportions with decreasing grain size of the clay it is likely to be formed, or at least to be stable, in that particular environment. If, on the other hand, its proportions decrease with decreasing grain size it may be unstable, and disappear the more rapidly the larger its surface per unit weight. Variations in mineral content throughout a profile, if a profile is developed, can be correlated with soil morphological data and with the ideas current about the formation of that profile.

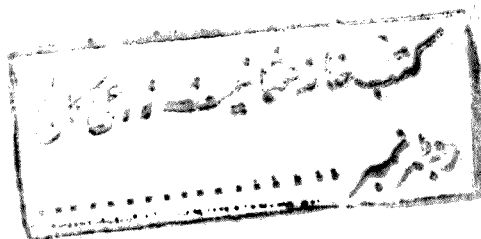
Hosking found Australian soils derived from basalt (basic rock) to give kaolin in soils with good drainage, but montmorillonite

in soils with poor drainage. This shows the predominance of the climatic-topographic factor over the parent material. This point has been stressed by Sedletzky in his first law of colloid-dispersion mineralogy that "the composition of the colloid-dispersive minerals in friable rocks is in no way determined by the initial rock, but solely by the character of the weathering process."

In soils from Java, Hardon found kaolin to be the chief clay mineral of lateritic soils, regardless of parent material. He found montmorillonite in marl soils classed as regur, but he also found a few soils where both minerals occurred together; these were either young soils or subject to flooding with river-borne alluvium, and would thus represent examples of explicable deviations from the general rule.

The mineral compositions of the clays from a red earth and a black cotton soils occurring in close proximity in the field were determined by Nagelschmidt and others. Both soils are derived from the same or from very similar parent rocks, a coarsely crystalline granite or gneiss. For both soils there is practically no variation in the mineralogical composition of the clay throughout the profile, but for any given clay there is some variation with grain size. The main contrast between the two is that the red clay contains predominantly kaolinite or halloysite, whereas the black clay contains mainly beidellite, a member of the montmorillonite group. The topography appears to be the principal factor associated with this difference in minerals.

Though the mineralogical composition of the soil is not yet regarded as suitable for using independently for the purpose of soil characterization, it nevertheless often serves to supply very valuable data to supplement the chemical and even the mechanical analysis. In many cases the proportion of easily to less easily decomposable minerals enables us to infer the degree of weathering undergone, particularly if we compare the mineralogical composition of the several horizons with the parent rock.



## *Soil Formation Processes*

THERE are six principal factors of soil formation :

- (1) Parent Material
- (2) Climate
- (3) Biological activity (living organisms)
- (4) Relief
- (5) Time
- (6) Man.

These soil forming factors are interdependent, each modifying the effectiveness of the others. Despite the complex interrelationships it is possible to gain a helpful insight into the question of soil formation by consideration of each of the formative factors separately.

(1) **Parent Material.** Parent materials have a strong modifying effect in many places on the type of soils developed and more especially on the rate at which development takes place. For instance, quartz and sands are much more subject to the dissolving effect of water than materials high in clays. This is because water passes easily through these materials and there is a smaller proportion of basic elements to be dissolved away. If calcareous cementing material is present in these sandy materials or if the rock contains large quantities of lime, removal by solution is very much delayed, but it is not necessarily prevented. Such rocks as shales, slates, silt, stones, phyllites, or mixtures of two or more of them may have the effect of checking internal drainage. This is especially true if the materials have been mixed and compacted by glacial action.

In the semi-arid and arid regions, parent-material clays sometimes become saturated with sodium and are often very impervious to water. These conditions favour the development of soils belonging to the Solonetz and Soloth groups (*see* Chapter XII). Heavy, waxy clays, whether calcareous or not, are very resistant to soil-

forming processes and may retain their essential parent-material nature throughout long periods. Sandy soils develop from very sandy parent materials quite regardless of the other conditions.

The residual effect of limestone on soils has its limits. For example, in warm-temperate and sub-tropical regions the prevailing type of weathering has so completely removed the lime and absorbed calcium from the soils that their fertility is greatly reduced. Eventually soil-forming processes overcome the beneficial effects and to a less extent the detrimental effects of parent materials. Effects of parent material are far more important on young and imperfectly developed soils than on old ones. Freshly deposited alluvium is an excellent example of this.

(2) **Climate.** Climate influences soils both directly and indirectly. Regions of high humidity have more highly leached soils than those of semi-arid and desert regions, and for this reason the chemical nature of the soils is radically different. In humid regions most soils are more or less acid in reaction and with few exceptions contain very little free calcium carbonate. On the other hand soils of the deserts are leached but little and usually contain more or less lime and, in many cases, some soluble salts. These effects are in large part directly attributable to climate. In the arctic regions where substrata are frozen throughout the year and where upper horizons freeze and thaw during warmer seasons, there is considerable mechanical mixing of the soil horizons, and the soils remain in a poorly drained condition most of the time.

The most important direct effects of climate are on the weathering of rocks and alteration of parent material. These points have already been discussed in some detail (*see* Chapter III). It is largely this direct influence of the climate on parent rocks which is responsible for the development of enormous areas of Laterite and old Red soils in the tropics. Many of these materials are true soils, but some of them are the parent materials of soils now formed or in process of formation. In some instances Laterites are true soils, and in others they are merely the parent materials from which new soil profiles are now developing.

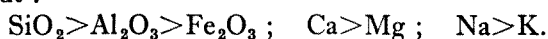
The main climate factors are :—

- (a) Rainfall
- (b) Temperature
- (c) Wind

(a) *Effects of Rainfall.* The total rainfall of a given region is not

necessarily a measure of the effectiveness of water in soil formation there. Long-continued gentle rains will moisten the soil much more effectively than torrential downpours. Gentle rains soak into the soil, and the water percolates downward without severe run-off, except where the parent materials are almost entirely impervious. On the other hand torrential rains tend to puddle the surface soil and prevent further penetration by water, and the rain runs off over the surface and into streams. If the land is not protected by vegetation or by erosion-control structures, soil erosion (*see* Chapter XXIV) may be severe even on some of the less readily erodible soils. The more gentle rainfall characteristic of western Europe as compared with the United States accounts in part for the relatively small amount of soil erosion in England, France, and Germany. Gentle rains are more characteristic of humid regions than of semi-arid climates, where torrential downpours are the rule. Heavy thunderstorms during summer months in humid regions are an exception to the rule, but their effects are partly offset by the absorptive qualities of the soils engendered by dense vegetation.

The most mobile constituents of the soil are the chloride, sulphate, potassium, and sodium ions ; calcium comes next, then silica liberated from the complex silicates ; all these appear in the drainage water, and are carried down to the rivers and finally to the sea. The least mobile are the oxides of iron and aluminium, the quartz and possibly the kaolin. Polynov gives the following relative orders of leaching out :—



In consequence of the difference in solubility of silica and the sesquioxides the ratio  $\text{SiO}_2/\text{R}_2\text{O}_3$  in the residual material falls during the leaching process ; in the original rock it may be about 6 ; in many soils it is about 4, and in extreme cases it falls to 2 or less.

The soil climate itself, especially that of the surface soil, has a great effect on soil formation and is profoundly affected by relative atmospheric humidity. Where the average humidity approaches complete saturation (90 to 100 per cent.) soil climate is more moist than when the average is 60 per cent. or less. The effects of relative humidity are especially noticeable in China. On the Kweichow Plateau and in parts of Kwangsi and Szechuan the relative humidity for the entire year averages approximately 95 per cent., and soils are in an almost continually moist condition in spite of the fact that the rainfall is less than in some regions where average humidity is lower.

A direct result of this difference in humidity is the formation of Podsollic soils. In the province of Yunnan, adjoining Kweichow on the west, relative humidity averages from 60 to 70 per cent. for the year, but the rainfall is greater than in Kweichow. In spite of a greater rainfall, soil humidity is less than that in Kweichow, and as a result the dominant soils belong to the Reddish-Brown Lateritic and Red Podsollic groups.

(b) *Effects of Temperature.* High average annual temperatures encourage the rapid weathering of parent rocks and soil materials. In general the speed of chemical reactions approximately doubles for each rise of  $10^{\circ}$  C. in temperature. Hydrolysis, carbonation, and other forms of chemical weathering are extremely rapid in warm regions, especially if those regions are humid. In dry hot regions dehydration is important and hydrolysis, hydration, and carbonation are slowed down. These processes are active only in deeper horizons where soils are protected from the burning rays of the sun and from the evaporation effects of winds. In cold regions, especially if they are humid, soils are frozen during several months of each year, and in arctic regions deep substrata are permanently frozen. Freezing prevents the percolation of water through the soil and so slows down soil-forming processes. In the tundra, processes of soil development are reduced to a minimum. In cool-temperate regions they can proceed actively only during the warmer months. Structure of soil is greatly modified in cool-temperate and temperate regions by freezing and thawing during transitional periods between summer and winter. Freezing and thawing of wet clays tend to form the material into aggregates.

The amount of water percolating through the soils depends partly on the rainfall and partly on the temperature. At Rothamsted approximately 50 per cent. of the rain falling on uncropped land soaks through on the average. In warmer conditions, however, the percolation is less: an increase of  $1^{\circ}$  C. in the annual temperature at Rothamsted lowers it as much as a reduction of 2.5 cm. in the mean annual rainfall.

This effect of rainfall in masking temperature may explain the interesting observations of J. van Baren that the weathering of limestone follows very similar lines in tropical India and in temperate Holland.

(c) *Effects of Wind.* In soil formation, wind acts as a drying agent and as an agent of erosion. Moving air will absorb more water than

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quiet air, so that in windy regions soils will dry out much more rapidly than in regions of calm. The effect is accentuated if the average relative humidity is also low.

Wind erosion amounts to very little in regions of heavy rainfall and dense vegetation, but it is extremely important in the desert and to a less extent in semi-arid regions. Winds pick up fine particles of soil and blow them from the deserts to nearby areas where vegetation is more dense and is able to hold soil in place. For this reason deserts are characterized by large expanses of bare rock, by drifting sand dunes, the grains of which are too heavy to be carried far, and by desert pavement.

Desert pavement is an accumulation of gravelly or stony rock fragments on the surface of soils. It is seldom more than an inch or two in thickness. Desert pavement is the coarse residue remaining on the surface after the fine particles of soil have been blown away by the wind. When it becomes thick enough to cover the soil completely it prevents further wind erosion. It will form only in places where the soil is composed of a mixture of fine-grained and coarse-grained materials. For this reason we do not find desert pavement on loess deposits or on silty or clayey alluvial materials. It is not common on soils derived from uniform-grained sandstones but develops readily where soils are derived from conglomerates or from interstratified gravels, sands, silts, and clays of alluvial fans.

(3) **Biological Activity.** Two of the chief functions of plant and animal life, so far as soil profile development is concerned, are the furnishing of organic matter for the soil and the bringing in of plant nutrients from the lower layers to the upper ones. It may be said that there is no soil without organic matter, but the organic-matter content of soils varies widely. Certain peats and the organic mats of some of the forest floors consist almost entirely of organic materials. On the other hand some of the desert soils contain only a small fraction of 1 per cent. of organic matter. The effects of organic matter upon soil profiles are also extremely variable. The primary source of soil organic matter is the vegetation that develops on it and modifies the colour of practically all soils. Higher plants, such as grasses and trees, drop their dead leaves and trunks on the surface, and these furnish an enormous quantity of organic material over a long period. The roots of these plants permeate the soil, making it more or less porous and penetrating it sometimes to depths of many feet. The decay of roots, especially those of grasses, provides a large

amount of organic matter for the soil. Organic material from grass and tree leaves is eaten by worms and mixed by them with the mineral soil.

Deep-rooted plants, such as some of the trees and grasses, bring water from deeper horizons to the surface and into the stems or trunks and the leaves of the plants. With this water there is always a certain amount of dissolved mineral material, particularly of more or less soluble bases, some iron and alumina, a little silica, and many other elements in smaller amounts. When the leaves fall and the plants themselves decay, these minerals are returned to the surface of the soil, and in this manner an important upward movement is established from deep horizons and parent materials to the surface. The process tends to keep the soils in a productive state, and the plants thus assist in the perpetuation of conditions under which they can exist.

The decay of forest debris causes the formation of organic acids of various kinds, including particularly carbonic acid. These acids in solution hasten the leaching processes of soils and soil materials and basic elements are rapidly leached away. It is the rule, rather than the exception, to find more or less strongly acid soils in humid forested regions. Desert vegetation is very scanty, as a rule, and plays a less important part in the formation of desert soils than of the soils in humid forested regions and especially in those of the sub-humid and semi-arid grasslands.

Animals play a role of secondary importance in soil formation, but their total influence is very great. They furnish one step in converting plant remains into soil organic matter, inasmuch as plants directly or indirectly furnish the food for animals and the excreta of the latter are returned to the soil, where they are further transformed. Barn-yard manure is an important source of organic matter in agricultural soils.

Burrowing animals, such as various kinds of rodents found in nearly all regions, aid in mixing various horizons of soils together and in supplying a certain amount of fresh parent material to surface horizons from which leaching in some soils is taking an extensive toll of plant nutrients. Earthworms feed on soil organic matter and thoroughly mix soils in which they live. They move and enrich many tons of soil to the acre each year, and they thrive especially well in moderately acid to moderately alkaline soils.

Micro-organisms play an extremely important part in the develop-

ment of soils. One of the most important functions of microorganisms is that of changing raw vegetable waste into soil organic matter. Putrefactive bacteria and various kinds of fungi cause the decay of dead leaves and other plant remains and aid in their incorporation into the soil as organic matter. Microscopic animals live on some of these plant remains and help convert them into soil material. Some nitrogen-fixing bacteria live in symbiotic relationship with plants, collect nitrogen from the air, and fix it in a form that can be used by higher plants. Nonsymbiotic nitrogen-fixing bacteria fix a still larger amount of atmospheric nitrogen in the soil. In general, fungi are more abundant than bacteria in forested regions, and their waste products are radically different from those left by bacteria. Conversely, bacterial activity is greater than that of fungi in grasslands. Nitrifying bacteria assist in producing nitrates from proteins and other nitrogenous compounds, so that they are available for the use of higher plants.

(4) **Relief.**<sup>1</sup> The influence of relief upon soil formation is due to its controlling effect upon drainage, run-off, and other water effects, including normal and accelerated erosion. Differences in relief may radically affect moisture and air conditions within the soil. Soil profiles on steep slopes are usually not strongly developed, except in some regions of heavy rainfall, warm climate, and dense vegetation. This stunting of soil development is due to (1) rapid normal erosion, (2) the reduced percolation of water through the soil, and (3) lack of water in the soil for the vigorous growth of plants responsible for soil formation. With equal rainfall and similar parent material, the soil climate is more humid on gentle than on steep slopes and still wetter on flats and in depressions.

The degree of profile development taking place within a given time on a given parent material and under the same type of vegetation seems to depend largely on the amount of water passing through the soil. With medium and moderately heavy textured parent materials, therefore, the most strongly developed soil profiles are found on flat areas where there is a sufficiently permeable substratum to carry off the excess ground water slowly. In poorly drained and waterlogged areas may be found strongly developed soils of a special type. Soils of flat areas in the humid temperate zone are characterized by leached surface horizons and extremely heavy subsoils of claypan or hardpan types. Convex, gently sloping areas in the same region have a similar sequence of horizons but are without the

extremely heavy development in the subsoil. These are sometimes called mature or normal soils. Normal erosion on them is just about sufficient to keep pace with soil-forming processes.

It has been pointed out that soils in semi-arid and arid climates usually contain more or less lime in the profile, especially in the lower horizons. They also normally contain some of the more soluble salts, such as the chlorides, sulphates, bicarbonates, and carbonates of sodium and other alkali or alkaline earth metals. On convex surfaces, where drainage is good, gradual leaching of rain water removes these salts to deep horizons, below the true solum<sup>1</sup> where they have no bad effect on crops. On concave or flat surfaces, where drainage is imperfect, saline solutions are held within capillary reach of the solum and the salts are precipitated on or near the surface by the evaporation of the capillary water. For this reason, micro-relief (minor variations in relief) is extremely important on soils of the semi-arid and arid regions, especially where irrigation of the land tends to raise the ground-water level.

Not only is the degree of slope important, in that it affects moisture conditions in the soil, but its direction is also significant, especially on the great plains and deserts. On moderate to steep northerly slopes of the Northern Hemisphere, the sun's rays are much less effective in heating the soil and evaporating the moisture than on southerly slopes. As a result soil moisture is higher on the northerly slopes, vegetation is denser, and the soils are darker.

(5) **Time.** Time is necessary for the development of soils from parent materials. The length of time required for the formation of a given type of soil depends largely on the other factors involved. Certain acid soils characteristic of humid regions form in a relatively short time on acid materials containing an abundance of quartz sand and a covering of dense forest growth, especially under a cool and very humid climate. Perhaps 100 or 200 years might be sufficient under such conditions. If lime is present in the sandy material the time requirement is greater, and if the texture of the parent material is very heavy, a very long time would be required, because of the difficulty of establishing and maintaining a free downward movement of water through the solum and into the parent material.

The time required for the development of a normal soil is probably greater in dry regions than in more humid ones. Where

<sup>1</sup>The solum is the true soil or that part of the soil profile that shows the effects of soil-forming processes. It lies directly over the parent material.

rainfall is light and vegetation scanty, the desert winds are active in removing and redepositing soil materials. Hard lime accumulations, many feet in thickness, have developed in these desert regions, but the time required must have been great.

Soils of high and steep mountains are normally young in terms of years and stage of development because of rapid erosion, and the age of soils on flood plains is also slight because of the almost continuous accumulation of materials. Many young soils of the mountains as well as of the flood plains are very fertile, but steepness, shallowness, and stoniness in the mountains limit their usefulness for agriculture. Young soils of alluvial flood plains include much of the most productive soil of the world.

One cannot make any useful statement in terms of years, however, regarding the rate of soil formation in general. Some soils have formed very rapidly, in a few years, and others exceedingly slowly. It is also clear that there is no direct relationship between the age or maturity of soils and the age of the rocks underneath.

The formation of the soil does not come to a standstill even if it is well developed: podsoles, for instance, may in time change into peat soils or steppe soils. From alkali soil we may get either acid, degraded alkali or regraded alkali soil. In such cases it is quite impossible to ascertain which state of the soil is the end of the process of development. And when a soil reaches a stage of stability, it has ceased to be a soil and has again become a rock.

It should be noted, further, that by "time" it is not meant an absolute period, but merely the stage of development.

(6) **Man.** Ramann was right when he affirmed that man is one of the most effective soil-forming factors, since it is in his power to change and replace the natural flora and fauna of the soil.

It is true that pedological textbooks have had little to say about this very important soil-forming factor—a deficiency which is pardonable when we remember that man's activities as a soil-forming factor embrace the whole field of agricultural production. Indeed, certain chapters of applied pedology—e.g., soil cultivation, soil reclamation, etc.—deal exclusively with the effect exercised on the soil by man. We must, however, insist upon the great importance of man as a soil-forming factor; for unless we take that fact into consideration, many phenomena will be in apparent contradiction to the conclusions drawn from certain soil-forming conditions.

Man's influence on soil formation varies according to his manner of cultivating the soil. In this connection we may distinguish three degrees of cultivation—primitive, extensive and intensive agriculture.

### DEVELOPMENT OF SOIL PROFILE

The way is now clear to discuss the actual processes whereby the soil profile is developed, in other words, the processes whereby the weathered rock material is differentiated into the horizons characteristic of an actual soil.

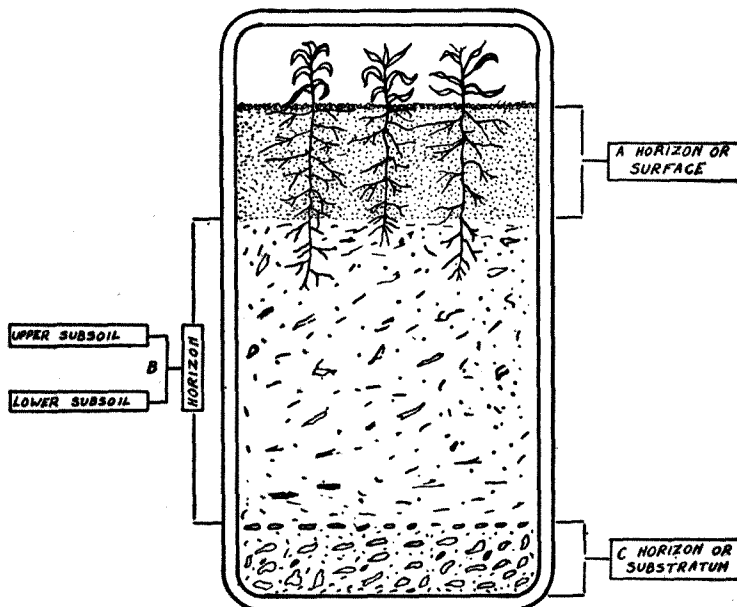


Fig. 17. A diagrammatic representation of a typical soil profile showing the various horizons.

If a section downward through a soil is examined, a well-defined layering will usually be found. Such a section is called a profile and the individual layers are regarded as horizons. Every well-developed undisturbed soil has its own distinctive profile. Such profile characteristics are made use of in soil classification and survey and are of great practical importance.

The upper layers of a soil profile generally contain considerable amounts of organic matter and are usually darkened appreciably

because of such an accumulation. Layers thus characterized are conveniently referred to as the A horizons and when ploughed and cultivated make up the familiar surface soil or furrow-slice. Below the surface soil lies the subsoil, also markedly weathered but usually containing comparatively little or no organic matter. Its various layers are referred to as the B horizons and extend to an indefinite but moderate depth below the surface. Here the noticeably modified subsoil gradually merges with the original regolith or parent material. This part of the profile is called the C horizon. It may be either unweathered or markedly weathered (*see Fig. 17*).

The A and B horizons together are called the solum, that is, the zone of definite soil building. The C horizon consists of noticeably less weathered material and is usually similar to or identical with that from which the A and B horizons were derived. As the C horizon, especially the upper part, may show some weathering, several zones may be distinguished. Generally, however, little attempt is made to differentiate within this horizon.

When virgin land is put under cultivation, the A horizon, in part or in whole, becomes the furrow-slice. The cultivation of course destroys the original zonal condition of this portion of the profile, the furrow-slice becoming more or less homogeneous. In some soils the A horizon is of sufficient depth to allow a sub-surface, but in many cases the plough-line is just at the top of or even in the B horizon. The B horizon is termed the subsoil, while the C horizon is designated as the substratum.

More attention is paid to the A than to the B horizon since most of the roots of higher plants are found there and it is from this part of the soil that much of the mineral nutrition is drawn.

Apart from the interference with the natural course of profile development occasioned by the process of cultivation and manuring, and the possibility of erosion after the removal of natural vegetation, the ordinary tillage operations cause a mixing of all the soil down to the limit of their action. And, therefore, if any vestiges of the original profile are to be found, they will occur below the depth affected by ordinary operations, i.e. about nine or ten inches.

Mature profiles are to be found, if at all, in areas of fairly level or gently rolling topography under natural vegetation which have been for long ages subjected to the pedogenic process characteristic of the locality. In some cases it may happen that profile development interrupted by erosion may be resumed on the establishment of a

cover of natural vegetation. This leads to the formation of secondary profiles, such as may be observed in some of the uplands of Wales, where grassland or heath has been established in the place of former forest.

As already pointed out, the development of a soil profile is mainly the consequence of movements of water in the soil, and we may distinguish three possibilities. Firstly, under humid conditions, there is an excess of rainfall over evaporation. There is thus a general tendency to downward movements of soil moisture, and the soil is subjected to a leaching process, whereby certain constituents are carried downwards and either deposited in lower horizons or completely removed in drainage. Secondly, under arid conditions, with an excess of potential evaporation over rainfall, such rain as falls moistens the soil to limited depths. After the cessation of rain, the soil moisture rises again to the surface under the influence of evaporation, with the result that translocation occurs alternately in both directions without any complete removal of constituents through leaching into the drainage. It should be added that evaporation is not necessarily confined to the actual surface, for when the moisture content is reduced to a certain point, capillary rise is inappreciable. And thus, in the final stages of desiccation, the deposition of materials from solution may occur throughout an appreciable depth of the surface soil. Thirdly, downward movement may be prevented by the presence of ground-water or by the occurrence of an impervious subsoil layer. In such cases, water movement can only occur laterally over the horizon of impedance. The impedance will not always be complete, and intermediate stages can be observed.

We may refer to the translocation of material, either mechanically or in solution, as eluviation, and two main types of eluviation may be distinguished, namely (*a*) mechanical eluviation, in which, apart from any chemical differentiation, the finer fractions of the mineral portion of the soil are washed down to lower levels, and (*b*) chemical eluviation in which decomposition occurs and certain products thus liberated are translocated in true or colloidal solution, to be deposited in other horizons.

**Mechanical Eluviation** results in the development of a texture profile, characterized by a light-textured A horizon from which clay and the finer fractions have been removed, and an underlying heavy textured B horizon enriched by the finer material eluviated from the

A horizon. It occurs when, owing to loss of crumb structure, fine material becomes mobile and is washed down in the profile to be deposited at lower levels. The increase in clay content in passing from topsoil to subsoil can be noticed in most profiles, but in some cases there may be a strong differentiation into a coarse textured A horizon and a fine textured B-horizon, which may form a clay pan of sufficient development to hold up percolation. Some of the best examples of such mechanical eluviation are found in the S.E. United States.

The intensity of mechanical eluviation depends mainly on the rainfall : but it is also affected by soil structure. A soil which maintains a well developed crumb structure is less subject to eluviation than a soil in which the single-grain structure prevails. The character of the clay complex and the base-status of the soil are of significance in this connection.

The formation of clay pans in mechanical eluviation has been studied by many workers. The process involves two stages, namely the dispersion of colloidal material in the A horizon and its deposition in the B horizon.

**Chemical Eluviation.** Whilst mechanical eluviation is governed chiefly by the intensity of the rainfall and the texture of soil on which it falls, chemical eluviation involves more factors. The following are the principal groups of constituents affected by chemical eluviation, and the distinctive characters of soil profiles result from their differential movements in true or colloidal solution :—

- (1) Soluble salts, such as sodium sulphate, sodium chloride, etc.
- (2) Relatively insoluble salts, principally calcium sulphate and calcium carbonate.
- (3) Exchangeable bases associated with clay and humus.
- (4) Hydrated alumina and hydrated ferric oxide.
- (5) Silicic acid.
- (6) Organic matter.

The simplest type of eluviation is that affecting readily soluble salts such as sodium chloride and sodium sulphate. Under humid conditions with an excess of rainfall over evaporation, these, if formed, are completely leached out from the soil profile. Under conditions of incomplete leaching, their presence in the soil profile gives rise to a distinctive group of soils which will be described later under the heading of saline and alkaline soils.

Next in mobility to the salts of sodium and potassium are calcium sulphate and calcium carbonate. Certain important groups of soils are distinguished by the development of horizons in which calcium carbonate and calcium sulphate are deposited in definite horizons. They are, like the saline and alkaline soils, developed under conditions of incomplete leaching.

In soil profiles of more humid climates, calcium carbonate, calcium sulphate, and the salts of the alkali metals are, in the absence of impedance, completely leached out of the exchange complex. This may proceed to such an extent that the complex loses stability and undergoes destructive decomposition, accompanied by a greater or lesser degree of differentiation into its components. Thus, in soils of extremely humid climates, not only are the soluble salts and calcium carbonate completely leached out, but the bases combined with the acid components of the colloidal complex are completely removed. Under these conditions the so-called humic acids become peptized as colloidal solutions and sink in the soil profile, where they become deposited as a humic B horizon. Under the same conditions sesquioxides also become peptized, and are also leached from the A and deposited in the B horizon below the humic B horizon. The eluviation of sesquioxides from the A horizon is shown by the development of a bleached layer, whilst their deposition in the B horizon is shown by the brown or yellowish-brown colours of hydrated ferric oxide. Such a profile is known as a podsol.

Eluviation does not consist necessarily in the downward translocation of material. Indeed, even where the nett movement is in a downward direction, as in the podsols, the actual deposition in the B horizon may take place from ascending solutions during periods of drought—a type of illuvial deposition which is even more pronounced in certain lateritic profiles. In those portions of the humid tropics which are distinguished by well marked wet and dry periods, mature soil profiles always contain concretionary material irreversibly deposited during dry periods from relatively concentrated soil solutions.

The presence near the surface of ground-water may lead to the development of a characteristic type of profile—the “gley” profiles of the mid-European writers. The alternation of oxidizing and reducing conditions in the zone of fluctuation of the water-table produces rusty deposits on the surface of the structural elements.

The horizon in which these deposits occur is termed the "gley" horizon. Drainage impedance owing to the impervious character of the soil itself may result in a diffuse horizon with mottling or staining. The changes occurring under submerged conditions are considered in a later chapter.

The organic matter profile is strongly affected by the character of the natural vegetation. Under coniferous forest or heath, the residues of vegetation accumulate as an acid peaty layer sharply distinguished from the mineral subsoil. Permanently wet conditions at the surface cause peat development. Under deciduous forest, plant residues, including leaf-fall and ground vegetation, are incorporated with the soil as "mild" humus, the dissemination through the soil being facilitated by the activity of earthworms. Under steppe, prairie, or savannah conditions, there is also a uniform distribution of organic matter corresponding with the root range of natural vegetation.

In order to illustrate the movements of these constituents, two examples of the development of soil profile under extremely arid and under humid conditions are described below. The mechanism of the formation of the various types of soils will be fully discussed later in the book.

**Soil Profile Development under Arid Conditions.** The entire story of soil development processes is best considered by describing the changes encountered in passing from the driest to the most humid climate.

Under desert conditions where rainfall is negligible in amount, it is evident that chemical decomposition can play only a very minor part. Physical weathering is here largely due to sudden temperature changes, and the agent of transportation is wind. The soils will chiefly be sands containing little or no colloidal matter unless such material had previously been laid down earlier in the same region when the climate was less dry.

Under less extreme conditions, in which the rainfall is sufficient to allow of plant growth, at any rate during part of the year, and evaporation is very high, quite different soils are produced. The water which saturates the soil during the rainy season has only limited opportunities for draining away because of the high rate of evaporation obtaining. During the evaporation the water is continually replenished from below and the substances held by it in solution are deposited at the surface of the soil. Thus the clay

material present is brought into contact with stronger and stronger solutions, chiefly of sodium salts. The calcium present in the soil water is transformed, on evaporation, from the soluble calcium bicarbonate to the very slightly soluble carbonate, another portion being deposited as gypsum (calcium sulphate). In the upper layers, therefore, the concentration of calcium ions will be low and practically constant, whilst that of the sodium will tend to increase. The colloidal clay itself will reflect this change; it will take up sodium as the exchangeable cation, releasing some of its calcium. A mixed sodium-calcium clay is thus produced. Such a clay is of a more sticky, impervious nature than a calcium clay and is characterized by the formation of a hard crust in dry weather. Agriculturally, therefore, these soils present very difficult problems in cultivation. In extreme cases the accumulation of salts in these saline, or white alkali soils makes plant growth impossible.

The washing out of the soluble sodium salts leads to further undesirable changes. The sodium clay then reacts with calcium carbonate to give sodium carbonate and calcium clay so that a strongly alkaline reaction is attained, sufficient to inhibit plant growth. The sodium carbonate dissolves humic matter which is brought to the surface and causes these soils to be described as "black alkali" (*see* Chapter 13).

#### **Soil Profile Development under Humid Conditions.**

Leaching with rain water removes soluble salts, the drainage water containing sodium and calcium in association with the nitrate, sulphate, chloride and bicarbonate anions. Further washing removes the bases from the clay and humus. Under these conditions hydroxides of iron, aluminium, and silicon are set free from the clay and are washed down to a certain depth, being protected from precipitation by the highly dispersed acid humus. Lower down they are deposited through the action of electrolytes in the sub-soil; the iron hydroxide may set to a hard layer called a "pan" which may prevent the movement of water and of plant roots. This is best seen on the permeable quartzose sands which are poor in base. Plant residues form a well-marked acid layer on the surface since the normal mixing activities of earthworms are precluded by the acid conditions. The soil thus assumes a banded appearance as shown in Fig. 18.

Podsolis are common on sandy soils in the colder and wetter parts of Northern Europe. These soils are very acid owing to the replace-

ment of the bases associated with the clay and humus by hydrogen from the rain water.

It cannot be too strongly emphasized that the soil profile, since it gives the summation of all pedogenic factors, including parent material, climate, vegetation and soil history, is the natural unit of soil study. Even where the natural profile has been partially

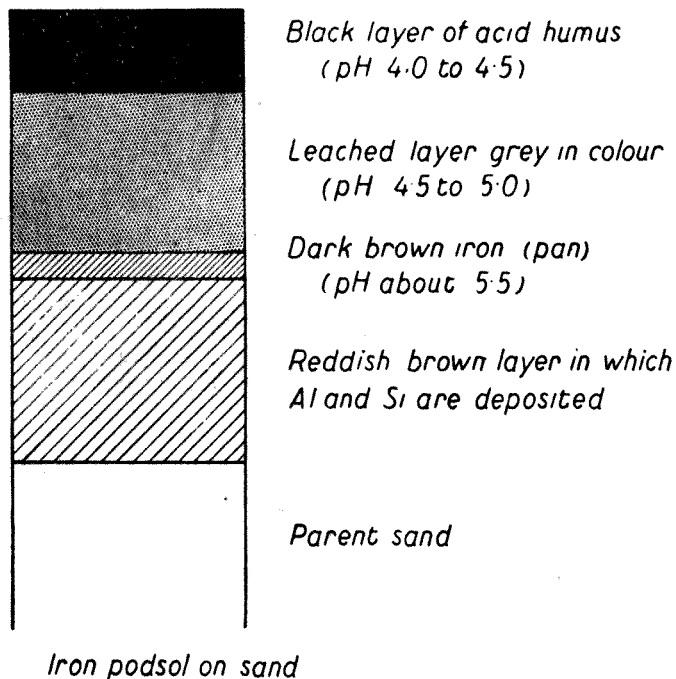
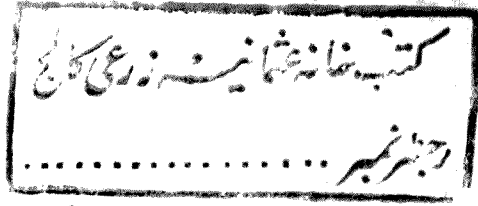


Fig. 18.

obliterated by cultivation or truncated by erosion, it is often possible to infer, from the profile thus modified, the character of the original profile. The general tendency of profile formation can also be observed in soils which have not yet attained their fullest development.



## CHAPTER 18

### *Soil Classification*

THE mineral substances on which the complex decomposing and leaching processes operate are very varied and in consequence the variety of soils produced is considerable. To study any heterogenous groups of minerals profitably some sort of classification is necessary. This is especially true of soils.

Soil classification is, however, rendered practicable by the circumstance that the redistribution of the products of decomposition and the effects of leaching lead to changes in the appearance of the successive layers of soil as one goes downwards. The top layer is darkened by the organic matter left by the vegetation : the lower layers vary in colour and physical condition according as they represent zones of loss of material or of decomposition. A profile is thus developed which records the history of the soil. These profiles form the basis of the morphological classification of soils which has been widely adopted. It is, however, now recognized that the account of the soil is not complete without adequate chemical examination of the successive layers. The actual appearance of the profile depends very much on the extent to which the iron has moved, but this is not an adequate measure of the leaching process. Further, the same general appearance of the profile may be associated with important differences in the chemical composition. Chemical characteristics are therefore now taken into account ; while this has made for greater accuracy it has also added a number of complications and it has raised many problems that have not yet been solved.

The value of experimental or research work of any kind is seriously restricted and may even be misleading unless the relation of one soil to another is known. Practical knowledge of crop relationships in any region is of uncertain application without some understanding of the formative processes of the soils in question and of their present profile similarities and differences.

The early recognition of soil differences was based on local observations and served local or limited purposes. Many were based on single features of the soil, such as texture or colour. These differentiations, while incomplete, were scientifically valid, since they dealt with true soil differences. The rise of geology as a distinct science with field methods and the recognition of the close relationship between soil and its parent material (in most instances the geological formation beneath it) led to a classification based on the composition of the underlying formations, such as the one defined by Fallou. Other systems of classification, based on factors lying outside the soil itself or only partly on soil characteristics, were also developed.

In Russia a sequence of profile types was observed in passing from the north to the south-east, and these soil zones corresponded with climatic zones. It was therefore assumed that for each type of climate there exists a stable equilibrium soil type and that given sufficient time the climate determines the soil type. Apparent exceptions were often explained by assuming a change of climate. On this basis climate maps and soil maps were interchangeable. Glinka published a forecast of the soils of Australia, and Shantz and Marbut (1913) one of the soils of Africa, in the latter case checking the map, however, by means of a few well-chosen samples taken by Shantz.

When soils are young the original geological nature of the soil materials and the conditions of position apparently determine the character of the soil. However, as time passes, climatic agencies become dominant, especially where the topography is level and erosion is slight, and geological differences tend to disappear. Thus most soils apparently are acquiring, some rapidly, some slowly, the characteristics induced by climate and its accompanying vegetation and are losing at a corresponding rate their original geological features.

Under such conditions soils over wide areas, varying greatly as to rock formations and geological origin in general, tend after a considerable lapse of time to become alike in general characteristics if the climatic influences are reasonably uniform and continuous and if erosion is not a serious factor. Thus climate becomes the first and the major factor to be considered in the initiation of soil classification.

Later work has shown, however, that the effect of water move-

ments in the soil is so pronounced as to cut across this simple generalisation. Nearly all soil types may occur in any one geomorphological region. Where drainage is complete and no water can come in from soil elsewhere, the bases are completely leached and acid soils are possible. Lower down, enrichment of the subsoil occurs as the result of seepage from above ; while still lower there may be accumulation of basic material or deposits of calcium carbonate.

A further objection to the purely climatic basis was that it left out of account the differences in chemical composition of the original rock, which, however, profoundly affect the properties of the resulting soils.

The purely climatic basis for soil classification has therefore been given up and instead the full description of the profile, including its chemical composition, is used. The profile records the history of the soil and as such forms the basis of modern classification. About 1870 a new school of soil science was founded in Russia under the leadership of Dokuchaiev. The scientists of this school recognized that each soil has a definite morphology, or form and structure, which is associated with a particular combination of vegetation, climate, relief, parent material, and age. They stressed the fact that soil is not a geological formation but an independent natural body, and they developed systems of classification in harmony with this new concept.

Soil classification is not, however, as clear cut as the classification of elements in pure chemistry or of plants in pure botany. There is nothing corresponding to a genus with its sharp limits that enable an expert to place individuals definitely into one or the other group. Every soil has something of the character of every other, and the classification is based only on the relative preponderance of one process over the other.

It should be realized at the outset that there are many possible systems, each of which may have a value for a particular limited purpose. From the philosophical standpoint, however, no system of classification can be considered satisfactorily which fails to express the genetic relationships of soils to each other. For example, a classification of soils according to texture, which would be quite adequate for practical purposes in a limited area, might lead to soils being grouped together which are completely unrelated genetically. The earlier attempts at soil classification were generally made with

a view to their practical significance, and it is only during comparatively recent years that the purely scientific view-point has secured general recognition in Western Europe and America. Perhaps the chief obstacle in arriving at a system of soil classification is the inevitably limited experience of individual workers. Another defect in earlier systems of soil classification lay in the restriction of attention to the surface soil.

#### EARLIER GENETIC SYSTEMS OF CLASSIFICATION

(1) **Hilgard's Classification.** E. W. Hilgard in America classified soils broadly into humid and arid, and showed by numerous experimental data the important differences between the groups thus distinguished. This classification, though valuable and valid, did not, however, greatly advance the solution of the general problem.

(2) **Ramann's Classification.** E. Ramann, in his classification of the soils of Europe, recognized with Hilgard the fundamental distinction of humid and arid soils. His first classification separates the soils in which the weathering is predominantly physical as in arctic and alpine regions from those resulting from chemical weathering. The former class include tundra and mountain soils.

(3) **Glinka's Classification.** It is probably mainly to K. D. Glinka of the Russian school that we are indebted for our appreciation of the importance of the profile in soil studies, since his ideas have exerted the greatest influence on the present generation of students of the soil. Glinka's classification is stated in terms of maturity of profile development and the intensity of leaching by percolating waters. The following is the classification proposed :—

I. Ektodynamomorphic soils (i.e., soils in which the external factors of the soil formation predominantly affect the soil character).

II. Endodynamomorphic soils (i.e., soils in which the parent material predominantly affects the soil character).

#### MODERN GENETIC SYSTEMS

(1) **Vilensky's Classification.** Recently, with fuller knowledge of the soils and of the pedogenic processes occurring in different parts of the world, systems have been proposed which aim at the inclusion of all possible types. Thus, D. G. Vilensky distinguishes four broad divisions of soils, based on the dominant factors in their formation. These are

- (1) Thermogenic
- (2) Phytogenic
- (3) Hydrogenic
- (4) Halogenic.

(1). Soils of the thermogenic divisions are developed in subtropical and equatorial regions, in which the dominant factor is the high temperature, which causes (a) rapid chemical decomposition of mineral silicates, and (b) rapid mineralization of plant residues with production of carbon dioxide. Under these conditions, red and yellow loams and laterites result.

(2) Soils of the phytogenic division are mainly developed in the temperate zones under a wide range of humidity. The dominant factor is the natural vegetation. They are characterized by conditions which favour the accumulation of organic matter in the soil, and involve a less intense weathering of mineral silicates than in the thermogenic divisions. These soils include the tshernosem and chestnut earth group, the degraded tshernosems, and the podsoles.

(3) Soils of the hydrogenic division are formed chiefly in cold climates, i.e., in the tundra and the adjacent forest regions. Soil formation proceeds mainly under water-logged conditions with the development of peaty humus. Ferrous compounds such as pyrites, marcasite, and ferrous carbonate, are found in the sub-aqueous horizons. These soils include the tundra soils, the peat podsoles, and the meadow soils.

(4) The halogenic division includes soils developed in the presence of sodium salts, and includes the saline, alkaline, and soloti soils.

Intermediate divisions such as thermophytogenic and thermo-hydrogenic are also distinguished.

Vilensky, later, developed and re-arranged his system in the following form, which throws into clear relief the relative parts played by temperature and humidity in soil formation. This system of classification is shown schematically in Table 24. |

(2) **Gedroiz's Classification.** An attempt to classify soils according to the character of the absorbing complex was made by K. K. Gedroiz, who first distinguished, (1) soils saturated with bases and (2) soils unsaturated with bases. The base-saturated soils fall into (a) the tshernosm group, predominantly saturated with calcium and magnesium, and (b) the alkaline groups in which sodium is dominant, including the saline, alkaline, and soloti soils.

The base-unsaturated soils fall into two groups, namely (a) the podsolis and (b) the laterites, including red and yellow earths, varying in the extent to which the weathering complex is decomposed.

Although Gedroiz's system is valid in itself, it seems scarcely detailed enough in its present form to serve as a world system.

(3) **Marbut's Classification.** During the past two decades, considerable discussion has been directed towards the institution of an agreed world system of soil classification. C. F. Marbut, at the 1st International Congress of Soil Science, held in Washington in 1927, proposed a system of soil classification to include all soils already known or likely to be encountered.

TABLE 21

*D. G. Vilensky's System of Classification*

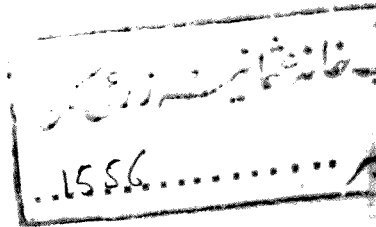
	Arid	Semi-Arid	Medium	Semi-Humid	Humid
Polar ...	Tundra	Semi-peat soils	Peat and meadow	—	Podsolized peat and meadow
Cold ...	Dry peat	—	Black meadow soils	Degraded meadow soils	Podsolized soils
Temperate ...	Grey	Chestnut earths	Tshernosem	Degraded (grey forest soils)	Podsolized soils
Sub-tropical	—	Yellow soils of dry steppe	Yellow earths	Degraded yellow earths	Podsolized yellow earths
Tropical ...	Red soils of semi-desert	Red earths	Laterite	Degraded red earth	Podsolized red earths

Marbut begins by making a division of soils into pedocals and pedalfers. Pedocals, which may be regarded as synonymous with Hilgard's arid soils, are characterized by the presence in the soil profile of a zone of calcium carbonate accumulation. Pedalfers, synonymous with humid soils, show no accumulation of calcium carbonate in the soil horizons, but show a differentiation or tendency to differentiation of the clay complex in the different soil horizons, resulting in accumulation of sesquioxides.

In the next stage of classification, the pedocals are divided into pedocals of the temperate zone and pedocals of the tropical zone, whilst the pedalfers are divided into podsollic and lateritic soils. The basis of classification in the second stage is, thus, temperature.

In the third stage of classification, the pedalfers are divided into the following groups :

- (1) Tundra
- (2) Podsoles
- (3) Brown forest soils
- (4) Red soils
- (5) Yellow soils
- (6) Prairie soils
- (7) Laterites
- (8) Ferruginous laterites.



The pedocals are similarly distinguished into :

- (1) North-temperate pedocals
- (2) Mid-latitude pedocals
- (3) South-temperate pedocals
- (4) Tropical pedocals.

It will be seen that, in this stage of classification, the distinctions made in the second stage are included.

In the fourth stage of classification, distinctions based on rainfall are used. In the scheme, as outlined by Marbut, this is only applied to the mid-latitude pedocals, giving the succession : tshernosem; chestnut earths; brown and grey (desert) earths. The information at present available does not permit a similar differentiation in the case of pedocals of warmer and colder climates. It is considered that this basis of differentiation may be applicable also to the pedalfers.

In the fifth stage of classification, soils are differentiated on the basis of the degree of maturity of the soil profile.

In the sixth stage of classification, distinction based on the parent material are used, giving the soil series, whilst in the seventh stage, the texture is used, giving the type. Marbut's classification is shown schematically in Table 25.2

It will be seen that spaces are left for the insertion of groups still to be identified and described, so that, with some necessary modifications, the scheme does give a basis for a world-wide system of

classification. According to G. W. Robinson no place is found in Marbut's classification for soils developed under conditions of impeded drainage, such as meadow and vlei soils. Such soils being intra-zonal or azonal, may not be considered as demanding a place

TABLE 2

*Scheme of Soil Classification by C. F. Marbut*

Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7
PEDOCALS	Pedocals of temperate climates	North temperate Mid-latitude	Tshernosems Chestnut-Earths Brown soils Grey soils	Sub-division of categories of Stage 4 according to maturity of profile	Sub-division of categories of Stage 5 according to parent material	Sub-division of categories of Stage 6 according to surface texture
		South temperate				
Pedocals of tropical climates						
PEDALFERS	Podsollic soils	Tundras				
		Podsols				
		Brown forest soils				
		Prairie soils				
	Lateritic soils	Yellow earths				
		Red earths				
		Laterites				
		Ferruginous laterites				

in the world-system, on account of their dependence on special local conditions of topography and drainage. They are, nevertheless, of widespread occurrence and according to G. W. Robinson should form a major group. ✕

(4) **Robinson's Classification.** G. W. Robinson is of opinion that our knowledge of the soils of the world is not sufficiently advanced for the formulation of an universal system of classification.

In the meantime, premising that the most fundamental distinction between soils depends on the character of the leaching processes, the well-known groups of soils might be conveniently tabulated as shown in Table 26. <sup>3</sup>

According to Robinson, the relative weight to be assigned to the factors geology, climate, and topography, will depend on the circumstances of a particular region or country. In Russia, for example, climate has proved the most fruitful principle of classification. In Great Britain, geology gives the clearest clue to soil differences. In every region, however, topography, as affecting the drainage and as modifying the depth of accumulation of the products of weathering, enters as an important factor in classification. The principle to be observed in every case is to classify on the basis of the soil itself, using the profile as the unity of study.

The provisional character of all methods of soil classification hitherto proposed cannot be too strongly emphasized. There are large tracts of the earth's surface where soils have been so imperfectly investigated that no trustworthy conclusions can be drawn as to their relationships. Even for the better known regions, the data are frequently of a qualitative character, and the deductions therefrom may be fraught with serious errors.

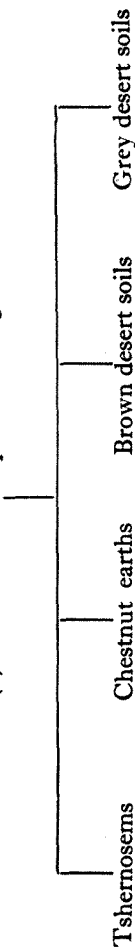
It may be doubted whether the classification of soils can ever be stated in terms of families, orders, genera, and species, as is possible in the case of animals and plants. Even if it were possible, the distinction between one soil species and another would be far more blurred than in the case of animal and vegetable species.

According to G. W. Robinson much remains to be done in the perfecting of a world-scheme of classification. The present deficiency results both from the incompleteness of the material and from the inherent difficulties of reducing this material to an ordered arrangement. In conclusion, one defect of existing schemes may be noticed. In nearly all cases, the ultimate soil-classes are named in terms of colour. Thus, we have red earths, yellow earths, brown earths, and black earths, as well as Russian terms such as podsol, tshernosem, and sierozem, which are also colour names. It is obvious that the description "black earth", whether in English or Russian, can apply to soils other than the tshernosem. Similarly, red earth, merely as a description, can apply to a wide range of genetically distinct soils. If a descriptive nomenclature is to be used, and this seems inevitable in a major classification, it might be better to sacrifice brevity for

TABLE 263

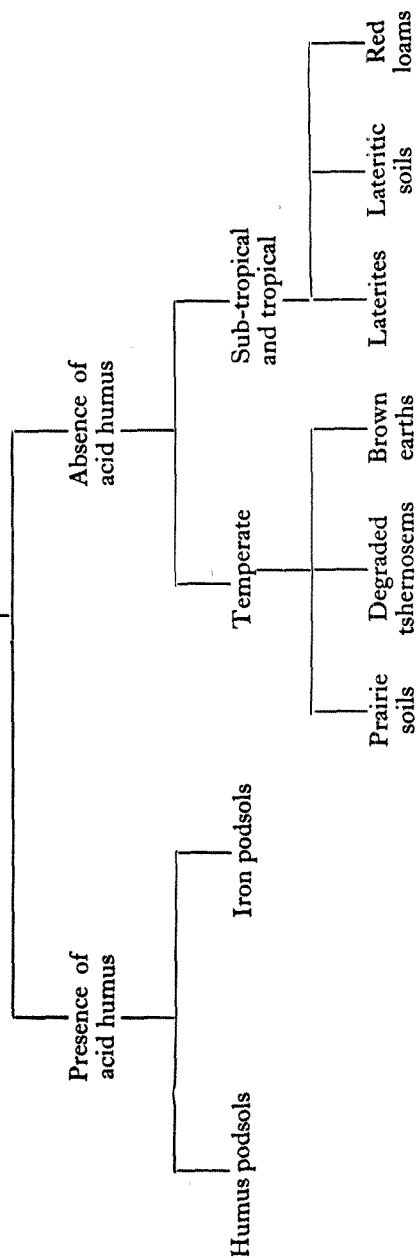
PEDOCALS

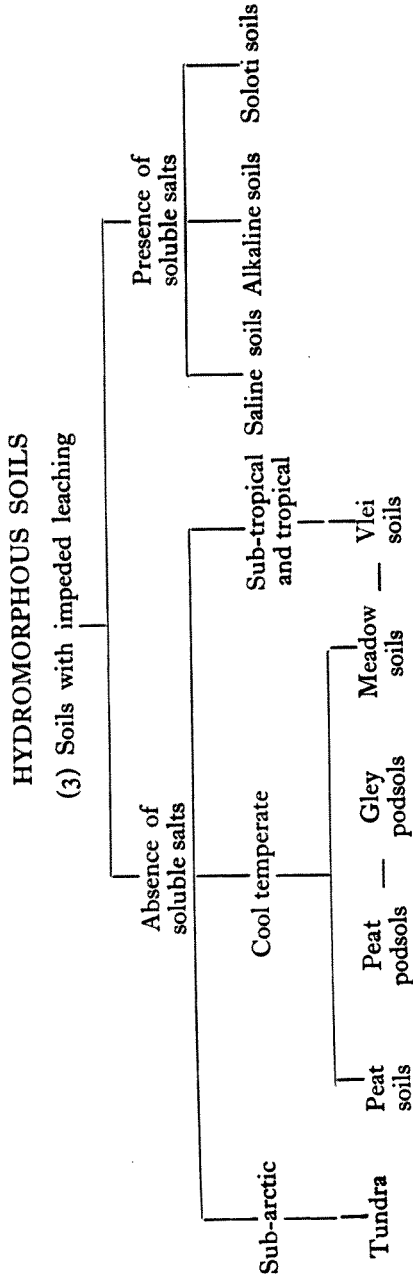
(1) Soils with incomplete leaching



PEDALFERS

(2) Soils with complete leaching





Such a scheme could be extended by the insertion of new groups when they are established.

precision, and to abandon podsol, tshernosem, and similar terms as scientific names.

### SIMPLE UNITS OF SOIL CLASSIFICATION IN THE FIELD

Three categories are commonly recognized in the classification of soils in the field—

- (1) Series
- (2) Type
- (3) Phase

The grouping of these units in higher categories will be dealt with presently.

(1) **Soil Series.** The most important of these field units is the soil series—defined as a group of soils having horizons similar as to differentiating characteristics and arrangement in the soil profile and developed from a particular type of parent material. Except for texture, especially of the A horizon, the morphological feature of the soil profile, as exhibited in the physical characteristics and thickness of the soil horizons, do not vary significantly within a series. These characteristics include especially structure, colour, and texture (except the texture of the A horizon, or surface soil) but not these alone. The content of carbonates and other salts, the reaction (or degree of acidity or alkalinity), and the content of humus are included with the characteristics which determine series.

Each soil in a series is developed from parent material of similar character. Parent material for soil is produced from rocks through the forces of weathering. Similar parent materials may be produced from different geological deposits and in different ways, and different parent materials may be produced from the same rocks because of differences in weathering. It is the character of the parent material itself which is important.

It follows that the external characteristics and environmental conditions of the soils within a series will also be similar. Each series has its characteristics range in climate and relief. Ordinarily the more strongly the soil characteristics are developed, the narrower is this range in external features. Except for young soils or those owing their distinctive characteristics to some unusual feature of the parent material, all the soil types within a series have essentially the same climate. It is to be expected, of course, that any differences in climate

or relief sufficient to influence the native vegetation significantly would be reflected in the internal characteristics of the soil.

Variations in texture, especially of the A horizon, occur within a series. In former years soils having considerable range in texture throughout the entire profile were sometimes included within a series. Significant differences in the texture of the B horizon or of the parent material are now considered to be sufficient grounds for recognizing new series.

The soil series are given names taken from place names near the spot where the soil was first defined. They are grouped in higher categories according to their characteristics. Several of the great soil groups include hundreds of soil series, differing from one another in important ways because of differences in parent material, relief, and age, but all showing the same general sort of profile.

(2) **Soil Type.** The soil type is the principal unit used in detailed soil researches. The definition of soil type is identical with that of soil series, except that the texture of the A horizon does not vary significantly. Thus, there may be one or more types within a series, differentiated from one another on the basis of the texture of the surface soil, the upper 6 to 8 inches. Since the greater part of the soil is directly involved in tillage and fertilization, special emphasis has been given to its texture.

In America attention has been directed to the determination and nomenclature of soil textural classes. The class name of the A horizon (or average of the surface soil to a depth of 6 to 8 inches in soils with weakly developed profiles), such as sand, sandy loam, loam, silt loam, clay loam, or clay, is added to the series name to give the complete name of the soil type. For example, Miami loam and Miami silt loam are two types within the Miami series. With the exception of the texture of the surface soil, these two soil types have the same differentiating characteristics, both internal and external. In Bog soils the word peat or muck, whichever is appropriate, is added to the series name to give the complete name of the soil type.

Within the range permitted in a soil type there may be small differences in climate-frostiness, for example—of much greater significance to crop plants than to the native plants. Similarly differences in relief, of little or no importance to the native vegetation, may be significant in the use of the soil when the land is cultivated. Such differences are recognized and mapped as phases of specific types.

(3) **Soil Phase.** A phase of a soil type, then, is defined on the basis of characteristics of the soil, or of the landscape of which the soil is a part, that are of importance in land use but are not differentiating characteristics of the soil profile. The three most important of such characteristics are slope, stoniness, and the degree of accelerated erosion.

Frequently soil types have no greater range in slope than that allowed within one slope class, but other soil types have a greater range, and in such instances the variations are recognized as phases. In a similar way phases are defined for differences in stoniness and accelerated erosion.

#### CLASSIFICATION OF SOILS ACCORDING TO PLANT FOOD RESERVE

According to de Sigmond, the quantities, solubility and availability of the various plant foods represent only a temporary cross-section of the dynamic system of a soil. Consequently, where we are not familiar with the whole dynamics of a soil, we cannot possibly decide to what extent the determined nutrient content may be taken as a criterion of the actual plant-food conditions. The dynamic character of a soil is best shown by the soil type. In many cases the total quantity of plant food suffices—e.g. in the humid tropical climate weathering and leaching are so active that even the fresh minerals and the organic nitrogen are readily transformed into available plant food. In temperate climate, however, the total amount of plant food usually informs us only of the soil's ultimate richness, and account must also be taken of the easily soluble or available nutrients which afford the vegetation the necessary nutrition. From the standpoint of practical agriculture there are four plant foods to be taken into consideration—N, P, K, and Ca. As regards the latter the mere determination of the soil type gives us some qualitative information, and it is only where there is a shortage of Ca that the amount required must be determined.

A shortage or abundance of nitrogen, phosphoric acid and potassium nutrients on the other hand does not materially affect the general dynamic character of the soil. Chernosems, for instance, which are usually rich in plant foods, may yet be deficient in phosphoric acid reserve. This does not affect their chernosem character, but where a steppe soil, for some reason or other, loses so much of its

calcium as to need liming it loses its steppe-soil character and becomes a degraded calcium soil.

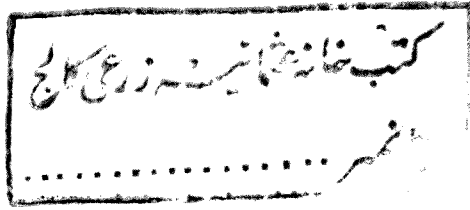
The physiological and chemical conditions of the soil also depend upon the character of the soil type. Chernosems are usually rich, not only in plant-food reserve, but also in soluble plant foods accessible to plants. To this must be added the peculiarity of these soils, so valuable from a practical standpoint, that the plant food once dissolved is not leached out, and in the event of its not being taken up by plants is absorbed by the soil. Virgin chernosems, when under cultivation, can dispense with all fertilization for a considerable time. Their only natural defect is a lack of humidity, which is very often the limiting factor controlling the quantity and quality of the yield. With varying local conditions the degree to which the plant foods are leached out also varies. Today it is common knowledge that chernosems are usually richer in easily soluble phosphoric acid, for instance, than the acid forest soils. But let us assume that the phosphoric acid soluble in dilute nitric acid is approximately the same in both. It may then happen that phosphoric fertilizers will have no effect on the forest soils, though very efficacious on the chernosems. This may be due partly to the acid forest being poor in other nutrients too, so that even the small available reserve of phosphoric acid is sufficient. Chernosems, however, are rich in other plant foods, so that the reserve of phosphoric acid, even if as large as in the forest soil, is nevertheless relatively small as compared with those of the other nutrients. There may, however, be another difference between the respective phosphoric acid reserves of the two soil types. Plants in addition to receiving food from the soil solutions, dissolve plant food themselves. This is particularly important in the case of chernosems, where there is usually sufficient finely dispersed lime present not only to protect the soluble phosphoric acid against leaching out, but also to impede its absorption by plants.

The object of the above illustration was to show that for the physiological characterization of a soil—viz., in respect of plant-food reserve conditions—it is necessary that we should be fully familiar, both scientifically and practically, with the soil type.

It suffices to determine the plant-food conditions in respect of N,  $P_2O_5$ , and  $K_2O$ , and on that basis to distinguish rich soils (soils not requiring fertilizers) and soils poor in certain nutrients (soils on which artificial fertilizers may be successfully employed). The determination of the above conditions may be effected in various

ways, and may extend also to measuring nutrient deficiencies. Too, many comparative experiments will be necessary to find internationally acceptable methods suited to different soil types. However, a suitable place had to be found for the plant-food conditions of soils, as they are important not only from an agricultural point of view, but also scientifically, for the soil is the natural source and store of plant foods.

It is interesting to note Mattson's view upon soils. According to him soils should be looked upon as parts or "tissues" of a larger body, the pedosphere. By a biological analogy the following division is made: The body = the pedosphere. The anatomy = the great soil groups. The morphology = the soil type as based on profile characteristics. The histology = the textural units. The protoplasm = the colloidal complex. The physiology = the soil solution.



## CHAPTER 19

### *The Great Pedocal Soil Groups of the World and their Development*

( UNDER arid conditions percolating rain water plays but little part in soil formation, its main action being simply to leach soluble salts from the surface to lower horizons. The primary processes are now the mechanical disintegration of soil particles by frost and wind, and the mechanical transport of these disintegrated fragments by wind or water erosion. Ground water, on the other hand, may have even more important effects on the soil profile than under humid conditions, for it can introduce salts into the upper horizons of the soil thereby causing fundamental changes.

Where evaporation predominates over rainfall, the state of affairs in the soil profile may be likened to that of a flower pot containing soil and watered so scantily that water never flows out of the drainage hole at the bottom. The soil is moistened to a certain depth and then dries out. This state of affairs is usually referred to as incomplete leaching.)

The main groups of soils of incomplete leaching which are called pedocals are :—

- (1) Chernozem soils
- (2) Serozem soils
- (3) Chestnut soils
- (4) Desert soils.

#### CHERNOZEM SOILS

We have chosen this particular group to start with, because the chernozem soils can be looked upon from many angles as ideal agricultural soils.

The original Russian term "tshernosem" for these soils has

now gained international recognition ; the terms "black earth" and "black soil" are not always used in a strictly identical sense.

These chernozem soils occur typically in south-eastern Europe and in the high plains of the United States. The climate, though dry, yields sufficient moisture to support a natural vegetation of grass and herbaceous plants in close cover. Carbonates are leached from the surface soil, but the base-status remains high. A constant feature is the presence of a zone of calcium carbonate precipitation at two to five feet from the surface. There is frequently an accumulation of gypsum below the calcium carbonate horizon. The calcium carbonate occurs, sometimes as nodules or concretions, sometimes as a filamentous deposit.

**Genetic Characteristics.** Chernozem soils are formed where there is a degree of humidity and a level of temperature sufficient to promote mineral weathering and humus formation, but without excessive soil leaching or the complete decomposition of organic matter. In these soils the alkali salts are leached out of the upper horizon ;  $\text{CaCO}_3$  is also more or less washed down into the lower horizons.

**Dynamic Characteristics.** The circumstances governing the formation of chernozems are such that the bases released during the weathering of silicates are only slightly leached out. The easily soluble alkali salts are leached out of the upper horizon—frequently indeed, out of the lower horizons too ; but the less easily soluble salts of Ca and Mg ( $\text{CaCO}_3$ ,  $\text{MgCO}_3$  and  $\text{CaSO}_4$ ) are only partly leached. Thus the decomposition of silicates is practically dominated by  $\text{Ca}^{++}$  ions, the first result being an absorbing complex saturated with calcium. Stebutt, indeed, says that in the natural state chernozems become richer and richer, because the steppe vegetation concentrates in the upper horizons the stock of plant food of the lower horizons. This is largely due to the saturation of the colloidal complex, principally with Ca, though partly also with Mg.

**Chemical Characteristics.** The consequences of the dynamic conditions described above are also evident in the chemical composition. The oldest chemical investigations showed that the composition of the mineral material remains practically unchanged throughout the whole profile. This phenomenon has often been erroneously interpreted as meaning that in chernozems there is no leaching, but as Kossovich showed, the slight leaching of bases is

counterpoised by their transport into the upper horizon by the rich vegetation. Thus, leaching, particularly of the water-soluble sodium salts, occurs in chernozem also, but it is characteristic for the leaching medium that it is dominated by calcium cations, the result being that the reaction is practically neutral or only slightly alkaline, for the soil contains a considerable amount of  $\text{CaCO}_3$ , the alkalinity of which in pure water corresponds to  $\text{pH} = 8.0-8.3$ .

One of the characteristic properties of chernozems is the remarkably high humus content, which in the case of the Russian chernozems most frequently amounts to 6-10 per cent. in the upper horizon (roughly 20 cm. in depth).

The humus of chernozems is saturated and stable ; consequently it hardly disperses or dissolves at all. The Russian scientists have always taken this circumstance into account and have determined the ratio of the water-soluble to the total organic matter. The proportion of water-soluble organic matter in Russian chernozems is 0.02-0.05 per cent., representing 0.5-0.7 per cent. of the total organic matter. The organic matter itself is absolutely homogeneous, without any trace of the original plant structure. It may be regarded as completely humified. The richness in organic matter is accompanied by a high nitrogen content—usually from 0.2 to 0.5 per cent., representing barely 5 per cent. of the total organic matter.

Owing to the high base-status, the humus is dark in colour, so that these soils appear black when wet, even when only moderate proportions of humus are present. However, in some Russian black earths the humus content may run up to 16 per cent. The layer showing the dark humus colour varies from  $1\frac{1}{2}$  to 3 feet in depth, and there is often an abrupt colour change to the grey-brown or grey material below.

Only the  $\text{CaCO}_3$  and the  $\text{MgCO}_3$  have been leached out into the lower horizons to any considerable extent, together with smaller quantities of  $\text{Na}_2\text{CO}_3$ , while the organic matter ( $\text{C} \times 1.72$ ) has accumulated in the upper horizons. This is confirmed by the hydrochloric extract analysis as shown in Table 27.

The essential point here is that the figures relating to  $\text{Fe}_2\text{O}_3$ ,  $\text{Al}_2\text{O}_3$  and soluble  $\text{SiO}_2$  remain practically unchanged throughout the profile, whereas in the case of forest soils and alkali soils, for instance, the above constituents migrate downwards and accumulate in the B horizon.

TABLE 27  
*Analysis of a tshernozem profile*

Analysis of the HCl Extract calculated to Soil dried at 105° C., in %						Percentage, Calculated to Humus- and Carbonate-Free Soil, 100					
Depth in cm.	0-30	30-60	60-90	90-120	120-150	Depth in cm.	0-30	30-60	60-90	90-120	120-150
Na <sub>2</sub> O ...	0.27	0.34	0.58	0.48	0.55	Na <sub>2</sub> O ...	0.30	0.40	0.70	0.58	0.67
K <sub>2</sub> O ...	0.58	0.54	0.51	0.51	0.42	K <sub>2</sub> O ...	0.64	0.64	0.62	0.61	0.51
MgO ...	1.65	1.98	1.73	2.66	3.10	MgO ...	1.50	1.76	1.23	2.25	2.44
CaO ...	4.51	8.06	9.22	9.12	9.71	CaO ...	1.68	1.00	1.38	1.27	1.18
MnO ...	0.08	0.08	0.12	0.17	0.27	MnO ...	0.09	0.09	0.14	0.20	0.33
Fe <sub>2</sub> O <sub>3</sub> ...	3.77	3.35	3.35	4.25	4.02	Fe <sub>2</sub> O <sub>3</sub> ...	4.17	3.99	4.04	5.11	4.93
Al <sub>2</sub> O <sub>3</sub> ...	5.47	5.11	3.69	4.01	3.94	Al <sub>2</sub> O <sub>3</sub> ...	6.05	6.07	4.46	4.82	4.83
SO <sub>3</sub> ...	0.10	0.11	0.13	0.16	0.17	SO <sub>3</sub> ...	0.11	0.13	0.16	0.19	0.21
P <sub>2</sub> O <sub>5</sub> ...	0.19	0.17	0.14	0.14	0.12	P <sub>2</sub> O <sub>5</sub> ...	0.21	0.20	0.17	0.17	0.15
CO <sub>2</sub> ...	2.67	6.24	7.13	7.20	8.09	—	—	—	—	—	—
SiO <sub>2</sub> ...	10.79	9.66	9.75	9.50	8.98	SiO <sub>2</sub> ...	11.94	11.53	11.77	11.42	11.01
TiO <sub>2</sub> ...	0.19	0.21	0.17	0.18	0.14	TiO <sub>2</sub> ...	0.21	0.25	0.20	0.22	0.17
Insol. residue ...	61.98	58.60	58.27	57.24	57.08	Insol. residue ...	68.58	69.89	70.37	68.85	70.04
Loss on ignition	7.79	5.40	4.93	4.62	3.67	Loss on ignition	4.56	3.88	4.48	4.55	3.79
Total ...	100.04	99.85	99.72	100.24	100.26	Total ...	100.04	99.85	99.72	100.24	100.26

These soils are 98-100 per cent. saturated, the Ca being the dominating cation in the upper horizon. The exchange capacity in the case of black soils is approximately 1 m.e. per gram of clay. It is also found that the black soils contain free carbonates (mostly calcium carbonate) varying from 0.4 per cent. to 25 per cent. and increasing with depth.

**Physical Characteristics.** The mechanical composition of chernozems varies considerably, a fact to be attributed to the varying character of the parent rock. However, as in the case of the chemical composition, there are no important differences in the mechanical composition of the horizons of any one profile.

Table 28 gives the mechanical composition of the profiles of some Hungarian chernozems.

TABLE 28

Soil	Depth of horizon (cm.)	Coarse sand (2.0-0.2 mm.)	Fine sand (0.2-0.02 mm.)	Silt (0.02-0.002 mm.)	Clay (>0.002 mm.)
No. (1) ...	0-30	2.9	47.8	25.9	23.4
	30-60	3.1	48.2	26.1	22.6
	60-90	2.0	46.9	30.3	20.8
	90-120	3.3	45.8	29.9	21.0
	120-150	2.9	47.1	29.7	20.3
No. (2) ...	0-30	1.8	55.4	27.9	14.9
	30-60	1.2	54.3	29.9	14.6
	60-90	2.0	51.9	30.8	15.3
	90-120	2.5	52.4	29.0	16.1
	120-150	2.2	52.5	30.4	14.9
No. (3) ...	0-30	2.8	56.8	26.2	14.2
	30-60	1.9	55.7	29.5	12.9
	60-90	1.6	56.4	28.3	13.7
	90-120	1.6	55.3	30.5	12.6
	120-150	0.9	56.1	28.9	14.1

The clay complex is of a siliceous type similar to that of the prairie soils. Chernozems have a fine granular structure and present little or no difficulty in cultivation. If the soil becomes impoverished in humus by long-continued exhaustive cultivation, the good granular structure may be lost. The soil is then subject to wind erosion during drought: witness the appalling dust storms of 1937 in North America.

The chernozems form a great belt running across Western Siberia, Russia, Czechoslovakia, Hungary, and in North America

running north and south through Manitoba, the Dakotas, and Iowa to Kansas. Other black soils also occur in this region, and it is impossible merely by casual inspection to say which are chernozems and which are not, though the differences are clear when a profile is examined and the necessary chemical examinations made.

The parent material is, in Russia and Europe, usually loess containing much calcium carbonate. In North America it is often ultimately of glacial origin and is poorer in calcium carbonate : this leads to differences between the two sets of black earths.

Apart from their liability to drought, the soils of this group are well suited for arable culture and, in particular, for long-term wheat growing. Some of the most important wheat areas of the world are on these soils. If exhaustively cropped they may deteriorate and suffer impoverishment in plant food and loss of the granular structure that renders them so easy to cultivate.

In climates drier than those under which black earths occur, similar profiles are found, but the organic matter content decreases and the colour of the soil becomes lighter, passing finally to the grey-brown or grey of desert soils. Drier climatic conditions are also associated with more marked development of the horizon of calcium carbonate accumulation, which also tends to occur nearer the surface, so that in desert soils it is close to the surface and may actually be at the surface when the overlying soil is removed by wind erosion.

An extensive investigation of chernozem soils was made by Nikoforov, who described them as follows :—

A : The humus horizon, which may be divided into  $A_1$  and  $A_2$ , the latter being more compact and of a somewhat darker brownish tinge, is dark grey or dark brownish in colour, black when wet, 40-45 cm. deep with a sharp line of division in colour and structure from the layer below. It varies in structure from a condition somewhat laminated at the top to lumpy granular at the bottom and when ploughed becomes powdery and lumpy. The horizontal cracking at the surface accentuates the laminar structure, giving the appearance of a layered formation.

The horizon immediately below, i.e. the horizon of illuviation, is more compact, ranging in thickness from 60 to 80 cm., and is divided into  $B_1$ ,  $B_2$ , and  $B_3$ .

$B_1$  : Compact, 15 to 20 cm. deep cracked vertically and horizontally, forming prismatic lumps. The cracking extends through the

next horizon of carbonate accumulation and even below that, and also to the top through the A horizon. On the walls of the structural prismatic units, glistening coatings of humus are noted. The humus follows the cracks in the profile giving it a characteristic appearance of dark streaks and tongue-like projections.

B<sub>2</sub> : This is the visible layer of calcium carbonate accumulation, 25 to 30 cm. deep. The lime spots are round in shape, 1 to 2 cm in diameter varying in consistency from soft to hard, and occur in large numbers so that from a distance it appears as a solid layer.

B<sub>3</sub> : A layer of gypsum occasionally with some soluble sulphates is found in this horizon. It occurs in the form of incrustations, irregular in shape, soft or hard, dirty yellowish in colour. Below the gypsum layer, just within the mellow parent material, black specks usually soft but infrequently of concretionary nature, are noted, probably manganese compounds.

The B horizon, because of the streaming effects of the humus and the distribution of lime and gypsum, is not uniform in colour. Generally the colour is yellow-brown. This horizon is sharply differentiated from C although the line of demarcation is not as well marked as that between B and A. Towards the bottom of this horizon the material has a tendency to crumble. In contrast to other divisions of chernozem in the U.S.S.R. the southern chernozem has but few crotoninas.

**Tropical and Sub-Tropical Black Earths (Black Soils).**  
In former times these soils were simply classified as chernozems, identical with the black earths of Russia. It was the "regur" soils of India that first attracted attention owing to their having been used for agricultural production for over 2,000 years without manure and without becoming exhausted. These soils are still the principal cotton-growing areas of India. Kossovich describes the "regur" soils as black earths which are clayey, heavy and sticky, being 1-2 (in exceptional cases 5) metres in depth, and having, here and there, a brownish or greyish tinge. Below these soils there is a loess-like parent material which rests on gneiss or trap. But in some districts the "regur" soil has developed directly from the weathered basaltic trap rocks. The annual precipitation is 1,200 mm., or even less—a very low rainfall for a tropical climate, particularly when we take into account the fact that there are alternate wet and dry seasons. This, indeed, is the reason why leaching is confined to the CaCO<sub>3</sub>, which accumulates in the lower layers in the form of concretions

known locally as "kunkar." Under natural conditions these soils are treeless and are covered with a grassy and shrubby vegetation. On drying "regur" shrinks and cracks to such an extent that it is often said that "black soil ploughs itself."

The climatic conditions for the Indian regur soils differ from those in the Russian chernozem region in that the temperature, even in the winter months, is always considerably higher. The rainfall, rather more abundant than in the Russian black earth region, is, however, insufficient to compensate for the great evaporation resulting from the high temperatures which prevail, and incomplete leaching results. The climate is thus not identical with that of the Russian chernozem region. Regur might, therefore, be described as tropical black earth.

The black colour is due principally to organic matter, as in the case of chernozems. Nevertheless, the high clay content of these soils and the frequent formation of cracks 12-15 cm. wide and 1-2 metres deep point to their structure being different from that of the Russian chernozems. It may be, of course, that the cracks are the result of the climate being warmer and more extreme.

Hilgard identifies the "regur" soil with the "black adobe" of California, though the latter is extremely difficult to cultivate, and has therefore very little in common with the black earths of Russia. Yet, although we are unable for the moment to define these tropical soils exactly, we may plausibly assert that they are calcium soils in which a considerable amount of mild humus accumulates.

In Morocco the chief belt of black soils, known locally as "Tirs," begins at the Tensift, the main river of south-western Morocco, and terminates in the north along the river By Regreg, which empties into the sea at Rabat. It covers an area 300 km. long and 50 to 60 km. (in some places 80 km.) wide. Fischer considers these soils as steppe soils. Along the Mediterranean coast, the black soils are found in island-like fashion among the red earths, but in the interior the steppe soils predominate. "Tirs" is generally not a deep soil: it usually extends down from 0.5 to 1.0 m., although in some places it reaches depths of 2 and even 6 m. During the dry summer the soil cracks, and during the winter rains the openings fill up with surface material. Its parent material varies from soft calcareous tuffs to sandstone, shales, clays, and other materials. Fischer associates the origin of the black earth belt in Morocco with loess formation. According to him the loess was blown in from the dry

steppe in the hinterland, caught by the vegetation, and fixed there by the heavy dews which fall in that region during the dry summer.

A good deal of Fischer's evidence is based on the numerous investigations of the French geologists. Of these, the work of Gentil is of interest. He compares the "Tirs" with the Russian chernozem.

Undoubtedly there are chernozem-like soils in the tropics and sub-tropics of South America. In the black earth belt of the "pampas" in Argentina, in Brazil, and in Western Australia as reported by Prescott. As yet no reliable data are available on the soils of these regions ; only after a complete profile survey has been made by trained pedologists will it be possible to chart the distribution of the various types and subdivisions within the chart.

Grey and black soils occur in Kenya which may also represent tropical chernozems. D. S. Gracie describes a group of soils, locally termed "black cotton soils," which appear to exhibit various

TABLE 29  
Composition of "Tirs"—black earth—from Morocco  
(After Fischer and Schwantke)

Constituents from a HCl extract	Sample from Abda	Sample from Schauia	Sample furnished by Fischer
	per cent.	per cent.	per cent.
N ... ..	0.110	0.023	0.089
P <sub>2</sub> O <sub>5</sub> ... ..	0.128	0.090	0.052
Ca ... ..	1.070	2.640	2.819
K ... ..	0.324	0.452	0.432
Mg... ..	0.727	1.368	1.359
SO <sub>3</sub> ... ..	0.172	—	—
Fe <sub>2</sub> O <sub>3</sub> ... ..	2.511	14.14	—
Al <sub>2</sub> O <sub>3</sub> ... ..	5.399		
H <sub>2</sub> O ... ..	5.876	—	3.131
Organic Matter ... ..	6.367	17.94	0.812*
Volatile substances ... ..	—		
Total ... ..	22.684	36.653	
Residue ... ..	77.316	63.347	
Residue from HCl extract : R <sub>2</sub> O <sub>3</sub> , Mn, and Na ... ..			10.378
R <sub>2</sub> O <sub>3</sub> : soluble in H <sub>2</sub> SO <sub>4</sub> ... ..			10.400
Alkaline earths and alkali : soluble in H <sub>2</sub> SO <sub>4</sub> ... ..			2.281
CO <sub>2</sub> ... ..			1.085
Sand ... ..			67.162
		Total ...	100.000

\* Designated as humus.

stages of degradation. In the undegraded type, the profile consists of a black clay, rich in exchangeable calcium, overlying a layer of calcium carbonate accumulation. In the degraded soil, there is a grey layer at the surface with acid reaction and low exchangeable calcium content. This overlies the black clay. A still further stage of degradation is seen in certain soils with acid greyish-brown surface horizons. Degradation appears to involve a loss of organic matter.

### SEROZEM SOILS

True serozems are principally cultivated irrigated soils, and may be divided into dark and light serozems. They are almost all calcareous chernozems, the exception being those developed on dolomite which contain large amounts of  $MgCO_3$ .

Phosphorus in serozems is present principally in the form of calcium phosphates extractable with 0.2 n. acetic acid. Organic phosphates form only 20 per cent. of the total phosphorus in these soils. They fix large amounts of added  $P_2O_5$ . Therefore soluble phosphatic fertilizers should be used, and the soil solution should be kept constantly supplied with  $CO_2$  by adding organic matter to the soil.

### CHESTNUT SOILS

These soils are characterized by a dark-brown or dark greyish-brown surface horizon grading into light-grey or white calcareous horizons at a depth of  $1\frac{1}{2}$  to 2 feet. The subsurface layer is brown, and the white calcareous layer lies at an average depth of about  $4\frac{1}{2}$  feet. These soils develop in temperate to cool semi-arid regions under a mixed short- and tall-grass vegetation. The principal crops are small grains. With an adequate moisture, they are highly productive, but average yields are low because of deficient rainfall.

**Genetic Characteristics.** As Glinka has shown, in these soils there is not sufficient humidity to support so luxuriant a grass vegetation as that found on chernozems. The result of this is that less humus is formed. The scantier the vegetation, the lighter the colour of the A horizon. As a consequence, a characteristic feature of these, as contrasted with other brown soils (brown forest soil, brown earths), is that their brown colour is due, not to iron hydroxide, but to organic matter. The soil humidity, is, however, enough to prevent the accumulation of alkali salts in the upper horizons.

**Dynamic Characteristics.** As a consequence of the origin of the soil type, leaching is restricted chiefly to the alkali salts, the  $\text{CaCO}_3$  and the gypsum being less intensively leached than in the case of chernozems. Another characteristic feature is that the gypseous horizon lies deeper than the  $\text{CaCO}_3$  concretions, as the gypsum is more easily soluble than the  $\text{CaCO}_3$  and the leaching is from top to bottom. Conversely, in all soils that suffer from excess of ground water and in which evaporation transports the salts upwards, the gypseous horizon is above the carbonate horizon. The sesquioxides and the soluble  $\text{SiO}_2$  are stable, as in the chernozems and other calcium soils.

**Chemical Characteristics.** In these soils the humus horizons are generally about 50-80 cm. thick ; the soils are low in humus and have a weaker macrostructure than have the chernozems. There is considerable differentiation of the salt profile, and primary silicates and carbonates of Ca and Mg accumulate in some of these soils. Saturation with Ca is 65-70 per cent. and with Mg 20-30 per cent. of capacity ; absorbed Na is less than 5 per cent. ;  $\text{SiO}_2/\text{R}_2\text{O}_3$  is about 3 ; montmorillonite and muscovite predominate in the clay minerals. The formation of dark chestnut soils is regarded as a stage preceding the formation of chernozems.

Table 30 contains the chemical composition of a typical chestnut soil profile. (Glinka.)

The proportion of humus in the chestnut soils ranges between 1 and 4.5 per cent., the humus layer generally being shallow.

**Physical Characteristics.** From the available data relating to the mechanical composition we can conclude that there is neither mechanical nor chemical eluviation in these soils.

## DESERT SOILS

Desert soils occupy vast reaches of desert or semi-desert regions. The climate is arid and cool to temperate. The vegetation is desert shrub, principally sage bush and shadscale. The surface-soils are typically light greyish-brown or grey in colour and low in organic matter. Subsoils are slightly lighter in colour and very limey. These soils are very little leached, are rich in mineral plant nutrients, and in places contain very high concentrations of soluble salts. Most of the land is useful only for live-stock range with low carrying capacity. Under irrigation these soils are highly productive of a wide variety of crops, including alfalfa, potatoes, small grains, vegetables, and fruits. Some areas are too salty or too alkaline to produce crops.

TABLE 30

Depth of Horizon in cm.	Constituents in the Original Air-Dry Soil											
	CO <sub>2</sub> %	H <sub>2</sub> O at 100° C. %	Loss on Ignition %	SiO <sub>2</sub> %	Al <sub>2</sub> O <sub>3</sub> %	Fe <sub>2</sub> O <sub>3</sub> %	CaO %	MgO %	K <sub>2</sub> O %	Na <sub>2</sub> O %	P <sub>2</sub> O <sub>5</sub> %	Total %
0-5.4	—	2.89	8.25	62.78	15.01	5.09	2.45	2.14	1.72	2.18	0.150	99.992
5.12	—	2.49	6.14	64.07	15.41	6.15	2.72	1.40	1.64	2.12	0.125	99.815
11.17	1.13	1.80	4.26	95.20	15.46	5.60	2.97	1.98	1.73	2.32	0.140	99.748
57.63	0.63	1.77	3.42	65.69	15.63	6.42	3.42	1.22	1.43	2.13	0.137	99.533

The following is a description of a chestnut soil profile.

A<sub>1</sub>: Usually somewhat greyish; the clods easily break into horizontal plates; at the surface it is frequently loose and finely powdered, about 10 cm. deep.

A<sub>2</sub>: It is of a looser constitution than A<sub>1</sub>, with a more conspicuous brown tint and small cloddy structure, about 10 cm. deep.

B<sub>1</sub>: Markedly compact, of a reddish brown tint, breaks into prisms or clods with sharp edges; about 13 cm. deep.

B<sub>2</sub>: The humus rapidly disappears, the structure becomes coarser, prismatic clods are apparent, and it effervesces strongly. Below this horizon there is accumulation of lime and even of gypsum.

**Genetic Characteristics.** Rainfall deficiency is the most characteristic feature of the desert type of soil formation. Few of the higher forms of plants or animals are encountered in the desert, and only the lower forms participate in the soil-forming processes. Very little biological weathering occurs there, and the little chemical weathering, which takes place independently of and simultaneously with the other processes of soil formation, is devoid of organic reactions. In general, it is primarily physical weathering that predominates in the desert.

Until quite recently it was believed that in desert climates, owing to the permanent and absolute character of the drought, there was not—and indeed could not be—any chemical weathering. However, the recent investigations of Blanck, Passarge, Kaiser, and others have proved that this supposition is mistaken. Even in the dry deserts there is some rainfall; and, though that rainfall may be very small when distributed over the whole year, the fact that periodically very considerable quantities of rain fall, combined with the high temperature, makes the effect much more rapid and more energetic than if the same quantities of rain were to fall equally under colder climatic conditions. We have already indisputable data to prove that not only the easily soluble salts but also the silicates weather and their constituents become mobile. Blanck and Passarge, for instance, have shown that a marl found in the Egyptian desert contains concretions, particularly of gypsum. In all probability the gypsum originated from the parent rock, being used to cement the finer particles on the soil surface. It is interesting, however, that in the finer particles the  $\text{SiO}_2$  appears to have increased and the  $\text{Al}_2\text{O}_3$  has decreased as compared with the parent rock. This cannot of course be proved as we have no exact data available.

In some of the desert soils the silica of the mineral matter has been partly mobilised. Here too we have very little reliable data available; but those which we do possess make it indubitable that in the case of the Egyptian soils formed from certain sandstones the finer weathered part contains far less  $\text{SiO}_2$  than the coarser debris. A similar regularity is observable also in the case of the Egyptian granite, pegmatite and gneiss soils. The decrease in the  $\text{SiO}_2$  is accompanied by a decrease in the amount of alkali salts, showing that weathering and leaching have taken place in an alkaline medium. This is probably one cause of the accumulation of  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$ , as it was in the decomposition horizon of laterites.

**Chemical Characteristics.** One of the most frequent peculiarities of dry, hot deserts is the accumulation of various salts. These are either residual salts produced by the decomposition of rocks or have been washed down by desert showers from more elevated places. As a consequence of the rapid evaporation of the water, the salts do not penetrate deep into the rock, but accumulate just below the surface, very often forming crusts. According to Mortenson the composition of these salt crusts may vary considerably. The following positive constituents have been detected: Na, K, Ca, Mg and more or less Ba, Mn and Fe, and other metal cations in negligible quantities. Among the negative constituents we find Cl,  $\text{SO}_4$ ,  $\text{CO}_3$ ,  $\text{PO}_4$ ,  $\text{NO}_3$ , Br, etc.

The variations, however, are not important enough from the standpoint of soil systematics to warrant our describing them here. According to de Sigmond, it is best to divide the salts into two groups determined by the measure of their solubility in water—viz., easily and slowly soluble salts. The easily soluble salts found most frequently in desert soils are NaCl,  $\text{Na}_2\text{SO}_4$ ,  $\text{Na}_2\text{CO}_3$  and  $\text{NaHCO}_3$  and the double salt of the two last. The water-soluble salts of K and Mg are much rarer, as is also  $\text{CaCl}_2$ . In exceptional cases we find accumulations of  $\text{NaNO}_3$ . On the basis of their chemical composition only, the salt-crusts soils in the tropical zone constitute a kind of continuation of the sodium soils—i.e. of the salty alkali soils. They differ from the sodium soils in general, however, in being in a very primitive stage of chemical weathering, only the most easily formed and easily transported weathering products—the alkali salts—having accumulated in any considerable quantities, and even the origin of these salts is obscure. In any case they originate from a larger weathering area than that in which they are found accumulated.

In many sections of the desert salts move from the lower levels to the surface. In some cases the cementing agents,  $\text{CaCO}_3$  and  $\text{CaSO}_4$ , form crusts. Not infrequently a flaky crystalline mass of NaCl and  $\text{Na}_2\text{SO}_4$  accumulates on the surface to be carried away sometimes by the winds. In this unique way the soil may lose appreciable quantities of easily soluble mineral salts. Crust formations extend also into the semi-desert region where rains do come some time during the year.

Besides calcium carbonate crusts, gypsum crusts with or without calcium carbonate have been reported. In some parts of Egypt

farmers mine this gypsum as it forms. Glinka cites Picard's analysis on samples of gypsum crusts from the North African desert : sand and clay—62.9 per cent.,  $\text{CaCO}_3$ —0.8 per cent.,  $\text{CaSO}_4$ —27.5 per cent.,  $\text{KCl} + \text{NaCl}$ —0.16 per cent.,  $\text{H}_2\text{O}$  and organic substance—8.64 per cent.

The accumulation of lime or gypsum on the surface indicates a phenomenon similar to solonchak formation, as pointed out by Blanckenhort. Fraas considered the crusts in Palestine as relics formed under conditions of a more humid climate. Passarge and Rolland shared this view also for the crusts in North Africa. Another example of this type of formation is the "caliche", a calcareous layer found in the desert regions of Nevada and other states.

Glinka believed that many of the described crusts "are true illuviation horizons, that others are eluviation formations and that the entire question needs further study." The "desert pavement" in Southern California, Nevada, and other desert areas in the United States are apparently examples of true illuvial horizons. The varnished and cemented gravel and stone of the "desert pavement" may be nothing more than an exposed layer, once covered with fine material and since carried away by erosion.

**Grey Desert Soils.** As we emerge from the true desert to areas where the rainfall permits sufficient vegetation to participate actively in the process of soil formation, we find typical soil development. We still encounter the desert pavement, but in the midst of the desert formations a characteristic soil type appears. In the desert and semi-desert regions of Turkestan the Russian pedologists have recognized the grey type of soil formation. In a different locality of a similar semi-desert the soil region is not grey in colour, but greyish brown to red.

The grey soil formations of the semi-desert regions have been studied very extensively by Neustruev and Dimo. According to the former a characteristic feature of this zone is the presence of calcium carbonate close to the surface, irrespective of the parent material, be it loess, alluvial clay, or conglomerate.

The lack of heavy surface growth excludes the formation of a typical  $A_0$  layer, a phenomenon true for grasslands in general. Organic matter is limited primarily to the  $A_1$  horizon, in the upper 10 cm., and does not go above the 2 per cent. figure. The following, taken from Zakharov, describes a typical grey desert soil profile.

$A_1$  : 0-10 cm. Characteristic straw-coloured-grey with various shades : yellow, brown, red, pink, scaly, laminated structure, fairly open constitution.

$A_2$  : 10-30 cm. A transition horizon, lighter in colour than  $A_1$ , at times having a brown shade ; of a spongy constitution, honey-combed with tracks of burrowing animals.

B : 30-80 cm. Illuviated, lighter in colour, usually straw-coloured, at times grey because of the numerous minute lime veins, more compact with a fine porosity. White spots known as "beloglazki"—white eye spots—are frequently encountered.

C : 80 cm. The parent material, at the surface of which sulphates and chlorides are frequently found alongside the lime carbonate.

A closer examination of the chemical composition of the grey desert soils also reveals a meagre differentiation of soil constituents in the profile. The water extract (Table 31) shows that even chlorides and sulphates, which are usually associated with the soils of the desert steppe, are low, and yet there is a definite increase of sulphates in the B horizon.

**Brown Desert Soils.** Dokuchaev, who observed the development of the brown soils in the region adjacent to the Caspian Sea, placed them into a distinct group. He differentiated the soils of European Russia primarily on the basis of colour and humus content, and in the case of the brown soils, he resorted to this method without a detailed study of their morphology.

The brown desert soils differ from the chestnut soils by their lighter brown-grey colour. Because of this grey shade, which, incidentally, is characteristic for all the soils of the semi-arid steppe, the humus horizon of the brown desert soils cannot be differentiated at times from the underlying horizon. The greyish brown predominates over the dark coloured humus which is not too abundant in the brown desert soils. On the average, brown soils contain 2 to 3 per cent. humus, and the chestnut brown 3 to 5 per cent.

In the United States typical brown desert soils are found in the eastern and western portion of Colorado, in Wyoming, Montana, and New Mexico. While on the trip with the First International Congress of Soil Science, the late Glinka pointed out typical brown soils at Ordway, Colorado. Vilenskii observed slightly solonetzic features in the brown desert soils of the same area. Zakharov gives the following morphological description of a brown soil profile :

$A_1$  : 0-15 cm. Humus horizon, straw-coloured-grey with a

TABLE 31  
*Water Extract of a Grey Desert Soil  
 (After Vituin)*

Horizon	Depth *	Reaction	Dry residue (per cent.)	After ignition (per cent.)	Loss on ignition (per cent.)	Mineral substances in dry residue (per cent.)	HCO <sub>3</sub> (per cent.)	Cl (per cent.)	SO <sub>4</sub> (per cent.)
A <sub>1</sub>	0-7	Alkaline	0.0552	0.0281	0.0271	50.91	0.0355	0.0014	0.0016
A <sub>2</sub>	13-26	"	0.0345	0.0254	0.0091	73.62	0.0344	0.0014	0.0010
B	50-60	"	0.0351	0.0290	0.0061	82.62	0.0368	0.0014	0.0046
C	103-110	"	0.0273	0.0188	0.0085	68.86	0.0307	0.0014	0.0011
C	172-180	"	0.0386	0.0267	0.0119	69.17	0.0376	0.0028	0.0020

brown or chestnut brown shade, laminated structure, friable with a finally porous constitution.

A<sub>2</sub> : 15-26 cm. Slightly compacted, a brighter chestnut brown shade, columnarlike, partly crumbly structure, slightly compacted and cracked.

A<sub>3</sub> : 26-45 cm. Lighter straw-coloured, with brown streaks and tongue-like projections, crumbly, nutty structure, more friable constitution, with many worm tracks.

B : 45-75 cm. Illuvial horizon, straw-coloured with white spots and veins of lime carbonate, slightly prismatic, porous and feebly cracked.

C : 75 cm. Loess-like or some other parent material which sometimes contains soluble salts.

The cotton soils of the Eastern Gezira in Sudan appear to be grey-brown semi-desert soils. They are developed from wind-borne material of rather heavy texture. The rainfall is about 400 mm. per annum, of which about two-thirds falls in July and August. The natural vegetation is sparse thorn scrub.

A typical profile, described by H. Greene, shows a surface soil of rather dark brown colour down to 2 feet. Below this is a grey layer which is penetrated by tongues of the top brown soil. In the upper part of the grey layer, ill-defined, detached lumps of grey soil occur surrounded by brown soil. Those nearer the surface contain small specks of calcium carbonate, whilst those lower down contain gypsum. At the lower limit of the grey layer, about four feet, white crumbly aggregates of calcium carbonate occur, amounting, at their greatest concentration, to 3 per cent. of the soil. Below this zone are crystals of gypsum in a matrix of yellow-brown soil.

The drying-out which occurs in the dry months of the year leads to the development of numerous cracks which extend for a considerable depth into the subsoil. These are filled with loose material blown from the surface by wind and there is, in this way, a certain amount of circulation within the profile.

The organic matter content is low—generally below 1 per cent., even in the dark-brown surface soil. In addition to gypsum, sodium salts are present and are closely correlated in amount with the gypsum content.

According to W. L. Powers, irrigation for a generation has changed a light grey-brown semi-desert soil to a dark chernozem-like soil.

## *The Great Pedalfers Soil Groups of the World and their Development*

PEDALFERS are widely distributed all over the world. Soils belonging to this group are to be found in cool temperate countries, as well as in tropical and sub-tropical regions.

The dominant factor in the development of these soils is complete leaching. The various divisions of this group of soils are schematically shown as follows :—

### (1) PODSOL SOILS

Podsol soils are developed in cool-temperate—occasionally in temperate—humid climates under the influence of coniferous, deciduous, or mixed forest vegetation. They are characterized in undisturbed forest areas by a surface mat of partly decayed leaves and wood fragments, over a light grey leached layer averaging a few inches thick, with or without a very thin dark-grey mineral humus horizon between. The upper subsoil is brown or dark brown, somewhat heavier textured than the surface soil, and grades through the yellowish-brown, moderately heavy, lower B horizon to the parent material. The solum is usually less than 3 feet thick. Most of the podsoles are strongly acid and have a low natural productivity for cultivated crops, but those having a texture as heavy as sandy loam or heavier may be limed, fertilized, and used for general farming and for grass and other crops in support of dairying.

This group of soils, by reason of its wide extent in Russia and Northern Europe, has received more detailed attention than any other group of soils, with the possible exception of the chernozems.

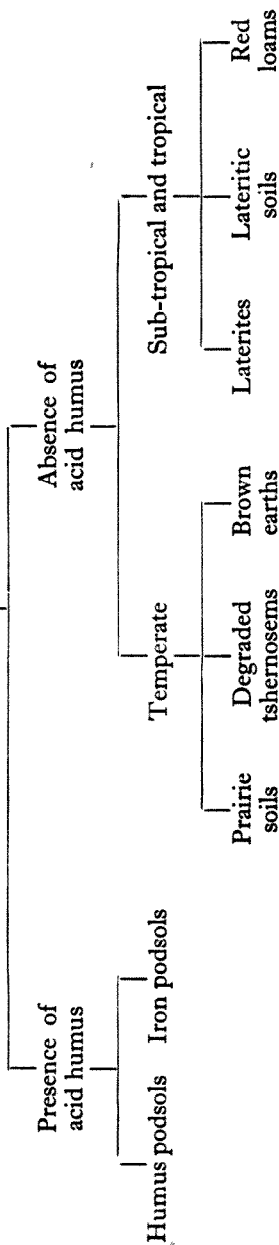
The essential conditions are :—

(1) Parent material containing neither limestone, dolomite nor possibly basic igneous rocks in any important quantity.

TABLE 32

PEDALFERS

Soils with ~~incomplete~~ leaching



(2) Little or no return of soluble material to the surface by the action of plants and earthworms.

(3) Sufficient excess of rainfall over evaporation to leach out basic material, and so permit the necessary acid humus to be formed and to persist.

(4) Sufficient highly resistant material such as quartz in the soil to serve as a framework providing pore spaces through which percolation can go on.

A typical podsol profile consists essentially of three horizons.

(1) **The A or Eluviated Horizon.** This consists of a layer of peaty material underlain by a more or less bleached layer, relatively poor in humus and sesquioxides.

(2) **The B Horizon.** This is enriched by certain of the constituents leached from the A horizon. The constituents are humus and sesquioxides. As the conditions of deposition vary with the relative proportion of humus and sesquioxides in the percolating moisture and also with its reaction, different kinds of podsol may be distinguished. In the more extreme types, the humus podsol, the B horizon is enriched by an accumulation of humus and sesquioxides, the accumulation of sesquioxides occurring at a lower level in the profile than that of the humus. In less extreme podsol, there may be no accumulation of humus, but an accumulation of hydrated ferric oxide in the B horizon. These are known as iron podsol.

(3) **The C Horizon.** The C horizon is the parent material from which the profile is developed.

Podsol is less readily developed in materials with high base reserves than in light quartzose sands. In loams and clays, the podsolized layer is shallower and indeed, in some cases, cannot be recognized without chemical analysis of the colloidal material. It is obvious, then, that the distribution of podsol is markedly influenced by geology.

### Classification of Podsol

(1) *Iron Podsol.* Variations in the amount of humus are responsible for two types of podsol much studied in Finland and the Scandinavian countries: the iron podsol, formed where sufficient humus is present for these various reactions, but no excess; and the humus podsol, formed where considerable humus is present, and the processes are therefore modified. These were first studied by Frosterus (1914). The iron podsol develops on porous, well-drained

soils containing but little humus, the water level remaining well below the surface. In these podsols the  $A_0$  horizon is relatively thin, not exceeding 8 cm. ; the  $A_2$  is fairly thick, especially on sandy soils, the B horizon, which is reddish-brown, does not contain more than about 3 per cent. of humus. In sandy soils a very hard dark brown pan may develop on the top of the B horizon, consisting of sand particles cemented together by the iron and humus that have been washed down.

(2) *Humus Podsols*. If, on the other hand, the soil is not well drained, or if the ground water level is near the surface during some of the year (though not for the whole year) the "humus podsol" of Frosterus is developed. The surface layer of humus is thicker—it may be as much as 20 cm. thick—and the  $A_2$  horizon is grey, but contains much humus which has percolated from above and deposited there. The lower part appears to the eye to belong to the B horizon, though chemical analysis shows that it really does not. The B horizon is dark brown and sometimes black on the top, due to the large amount of humus present.

(3) *Gley Podsols*. The precipitation of materials in the B horizon of podsols often leads to the formation of hardpan (ortstein). Such a condition may be followed by impedance of drainage and a change in the character of the soil profile to gley-podsol.

(4) *Truncated Podsols*. In hilly districts, soils are frequently encountered in which the A horizon has apparently been removed by erosion. G. W. Robinson describes such a profile at Aber, Caernarvonshire, England. It occurs under grass and bracken under a mean annual rainfall of 60 in. at 800 feet.

- 0-3 in. Turfy layer.
- 3-6 in. Dark brown turfy loam.
- 6-9 in. Brown loam.
- 9-12 in. Light brown, light loam.
- 12-15 in. Reddish-brown shaly loam on ordovician shale.

The principal analytical data are shown in Table 33.

### The Process of Podsolization

The first sign of podsolization is the appearance under the humus (A) layer of greyish leached strip ( $A_2$ ) very irregular, often barely distinguishable, and about 0.5 to 1 cm. thick. This bleaching is very superficial, and hardly affects the chemical composition of the

horizon. The leached out material is deposited immediately below in a layer (B<sub>1</sub>), which from the outset is much thicker (5 to 10 cm. or more). The deposition may be uniform, but it is more usually in spots and patches which, however, join up ultimately to a continuous layer. The important difference is that the leaching out proceeds by

TABLE 33  
*Analytical Data for Truncated Podsol*

Depth	0-3 in.	3-6 in.	6-9 in.	9-12 in.	12-15 in.
Organic carbon % ... ..	15.9	8.1	5.4		3.4
pH ... ..	4.20	4.42	4.58	4.78	2.82
Clay fraction : SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub> ... ..	2.17	2.25	2.17	1.95	2.12
"  "  SiO <sub>2</sub> /R <sub>2</sub> O <sub>3</sub> ... ..	1.63	1.69	1.62	1.48	1.50
"  "  Al <sub>2</sub> O <sub>3</sub> /Fe <sub>2</sub> O <sub>3</sub> ... ..	3.02	3.02	2.95	3.13	2.42

thin layers while the deposition is spread over a wider layer. As leaching continues the leached A<sub>2</sub> layer widens and it invades the B<sub>1</sub> layer ; thus B<sub>1</sub> is first a layer of deposition than of dissolution.

The process is fairly rapid. In some of the podsoles on the shores of Lake Ragunda in Sweden, the grey layer had attained a thickness of over 1 cm. in many places within the last 100 years. Muir records the formation of a layer of 0.5 cm. thickness within the last twenty years in Kincardineshire, Scotland.

TABLE 34  
*The Amount of Exchangeable Bases Present in a Podsol Profile (Gedroiz)*

Depth of Sample in cm.	Absorption capacity in milligram equivalents per 100 gm. of Soil	Percentage Composition of Exchangeable bases		
		Ca	Mg	H
10-15	12.1	13.9	7.5	78.5
15-20	4.6	20.8	8.4	70.8
20-25	1.8	40.5	20.1	39.4
30-35	4.3	50.1	43.7	6.2
50-55	11.9	49.5	46.9	3.6
100-105	12.4	54.6	41.5	3.9

In passing down the profile there is a fairly definite sequence of pH values. On the surface of the A<sub>0</sub> horizon the pH is always low, falling below 4 in extreme cases. The general tendency is for

the pH to rise with increasing depth, but often the A<sub>1</sub> and A<sub>2</sub> horizons are more acid than the A<sub>0</sub>. The B horizon is rarely more acid than pH 4.7.

The exchange capacity of the A<sub>0</sub> horizon is always high, through the presence of organic matter, and it may hold appreciable quantities of exchangeable calcium in spite of its acidity. The exchange capacity falls markedly in the A<sub>1</sub> and A<sub>2</sub> horizons, although the percentage saturation of the soil may be increasing; it rises again in the B horizon while the percentage saturation continues to rise.

W. Davies and G. Owen made extensive study of podsol soils in the North of England. Table 35 shows clearly the nature of podsolization.

TABLE 35  
*Analytical Data for Podsol Profile (W. Davies and G. Owen)*  
*(Shropshire, England)*

Depth of Horizon	Horizon	Clay %	Organic Carbon %	pH	Composition of Clay Fraction		
					SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub> /R <sub>2</sub> O <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub> /Fe <sub>2</sub> O <sub>3</sub>
0-9"	A <sub>0</sub>	2.7	14.88	3.70	3.13	2.55	4.43
9-19"	A <sub>1</sub>	1.3	1.63	3.13	2.81	2.66	18.00
19-23"	B <sub>1</sub>	8.8	7.14	3.73	1.79	1.66	13.03
23-35"	B <sub>2</sub>	2.2	0.40	3.75	1.51	1.19	3.80
—	C	3.3	0.04	4.75	2.29	1.94	5.54

The above data give a clear picture of the process of podsolization. In the first place, there is some evidence of mechanical eluviation in the rise in clay content in the B<sub>1</sub> horizon. Secondly, there is a marked rise in the organic carbon content in the B<sub>1</sub> horizon. Thirdly, the siliceous character of the clay fraction in the A horizons and the contrasted sesquioxidic character of the clay fraction in the B horizons should be noted. Finally, the strongly acid reaction of the whole profile, and the increase in pH with depth is shown.

An essential factor for podsolization is the presence of peaty organic matter such as occurs under coniferous forest or heath. It would appear that an acid reaction is not in itself sufficient to cause podsolization. This may be readily shown in the laboratory by allowing 0.1 N-solutions of hydrochloric acid and oxalic acid, respectively, to percolate through ferruginous sand. Although the pH of the hydro-

chloric acid is lower than that of the oxalic acid, the solvent action of the latter acid is considerably greater and quickly leads to a bleaching by removal of ferric oxide. H. T. Jones and J. S. Wilcox, from laboratory studies of the solution of sesquioxides in A horizons and their precipitation in B horizons, conclude that hydroxy-acids play a part in the solution of sesquioxides, which are translocated in combination as complex anions and precipitated as basic salts.

Although B is a horizon of accumulation, there is usually some loss by leaching of alkali and alkaline earth hydroxides and sometimes also of silica, alumina and iron, but the relative proportions lost depend on the ease of decomposition of the parent minerals.

Tamm estimated that the amounts of the various substances set free annually by the decompositions in the upper layer of a young podsol (about 600 years old) on river sand were :—

TABLE 36

	Grm. per Square Metre per Annum	Lb. per Acre per Annum
SiO <sub>2</sub>	5.9	53
Al <sub>2</sub> O <sub>3</sub>	2.2	20
Fe <sub>2</sub> O <sub>3</sub>	1.1	10
CaO	0.3	3
MgO	0.5	5
Na <sub>2</sub> O	0.3	3
K <sub>2</sub> O	0.5	5
P <sub>2</sub> O <sub>5</sub>	0.15	1.5

Further Tamm, K. Lundblad, and others using Tamm's acid ammonium oxalate method for determining the easily soluble colloidal material, have shown that the easily soluble Si, Fe and Al attain their maxima in the B horizon. This indicates that silica as well as the iron and aluminium moves down the profile.

The organic matter is no longer regarded as protecting the iron and aluminium sols from coagulation ; indeed highly dispersed humic acids in the leaching water appear to hinder the movement of iron and aluminium down the profile. On the other hand, diffusible organic acids such as oxalic, tartaric, and citric readily hydrolyse alumino-silicates and can dissolve the products of the hydrolysis to form co-ordinated complexes. The modern view is therefore that the decomposing organic matter on the surface of the podsol acts by furnishing a supply of diffusible acids that can move down with the

percolating water. Acid humus may also move down the profile, but it does not cause the hydrolysis or transportation of the silica, alumina, and iron.

The cause of the deposition of the hydrolysed material is still an open question. Mattson explains it by a hypothesis of isoelectric precipitation. The leaching of the organic acids sets up a steep pH gradient in the soil, the pH being low on the surface but higher lower down. The soil complex contains basic as well as acidic groups and it consequently functions as a base when the pH of the horizon falls below the isoelectric point ; in the surface layer therefore it ceases to act as an acid and becomes a base with which the percolating acids can combine. If the acids form undissociated compounds with the basic groups the system remains stable, but if they form dissociated compounds with the basic groups, these groups acquire a positive charge, and are dispersed and carried down by the percolating water. These basic groups are mainly aluminium and ferric hydroxides and silicates, with an isoelectric point considerably higher than the pH of the percolating acids. As the complex moves downwards the pH of the soil rises, the basic groups come nearer their isoelectric pH and lose their mobility some time before it reached. The soil acids become stronger in the A horizon, due to the loss of basic groups, and weaker in the B horizon, due to a gain in these groups.

**Podsols in Tropical and Sub-Tropical Regions.** Owing to the rapid destruction of organic matter in tropical soils by ants, micro-organisms, and other living things there is frequently insufficient humic acid to allow of podsolization even when the rainfall is sufficient. Podsols are therefore less common than in colder conditions and indeed they were at first regarded as essentially non-tropical soils. Mohr showed that podsolization occurred in Java, and although Sensius considered that these particular soils were not true podsols, subsequent investigation has proved beyond doubt that true podsols exist in the tropics. Wentholt found them in Northern New Guinea, Marbut described examples found in the Amazon valley, and Vageler has also given examples. No full investigation of the course of podsolization under tropical conditions has yet been made, however.

**Management of Podsol Soils.** According to Gratovskaia, correct manuring, liming and cultivation radically alter podsolized soil and transform them into regenerated soils, akin to chernozems.

Recent investigations on the causes of infertility of Quebec podsol soils showed that the treatment of typical lowland, sandy, podsol soils with sodium carbonate resulted in a marked increase in the yield of oats. A slight increase in soluble phosphorus compounds occurred when the action of sodium carbonate was prolonged. A direct solvent effect of sodium carbonate on the iron-containing compounds of the soils has been shown. Nauk has found that drying soils at 30-50° for 6 hours increased the fixation of phosphate ions in podsols and red earths. It is suggested that this increased absorption is caused by changes in the surface properties of soil colloids, degradation of the surface during drying increasing the capacity of phosphate to penetrate into the soil particles. Zanovich has also shown that podsol soils contained more mobile  $\text{PO}_4'''$  than did chernozems, but were less able to replace  $\text{PO}_4'''$  utilized by plants.

The reclamation of podsolized soil, however, necessitates three processes :—

- (1) The neutralising of the acidity.
- (2) The conversion of the acid humus and acid clay into calcium combinations.
- (3) The bringing up to the surface of the humus and other constituents that have been washed down.

The first and second require the same treatment, and are in the main the same thing. Lime, limestone, or chalk are added.

D. L. Askinazy and S. S. Yarusov show that the lime stimulates decomposition of the humus, enriching the soil solution in inorganic nitrogen and phosphates, and raising both yield and percentages of nitrogen and  $\text{P}_2\text{O}_5$  in the crop during the first year. The improvement in nitrogen supply became less as time went on and ceased entirely in the ninth year ; the improvement in phosphate supply, however, continued.

The bringing back of some of the material washed down from the surface soil is achieved by deep ploughing. Excellent examples of reclamation can be seen in Jutland, where the heaths are being converted into farms and forests by methods worked out by F. Weiss and his assistants.

An interesting example of reclamation of a podsol in New Zealand is furnished by the treatment of the Pakihi lands of the Nelson Province, a considerable area of land having all the characters of a humus podsol. Burning of the wild vegetation, followed by liberal treatment with lime (2 tons per acre) and basic slag (5 cwt.

per acre), then thorough disc cultivation, was sufficient treatment preliminary to sowing with mixtures of seeds and grasses : no deep ploughing or breaking of the hard layer was necessary.

On comparing different methods of cultivation Gladilovich found that deep ploughing and inverting the podsol horizon produced higher yields of spring wheat than did shallow ploughing. Deep ploughing and the use of manure and NPK fertilizers increased available nutrients and base saturation and decreased the acidity and available Fe content as compared with the untilled soil. Inverting the podsol horizon without the use of fertilizers, and shallow ploughing had a negative effect on the physico-chemical, biological and dynamic processes of the soil.

## (2) BROWN EARTHS

Akin to the podsol soils are a group of soils variously known as brown earths, brown forest soils, or grey-brown podsol soils. These are developed where leaching is less intense and soil conditions less acid, i.e., in warmer and drier climates or on less acid parent materials. The natural vegetation is deciduous forest or scrub. The humus layer is less strongly developed and the humus is of the "mild" type. There is no marked bleaching, although it is sometimes possible in the laboratory, if the humus is destroyed by oxidation with hydrogen peroxide, to distinguish a lighter shade in the surface soil. Removal of ferric oxide from the A and deposition in the B horizon occurs only slightly, if at all. At the same time, the profile shows brown or orange-brown colours owing to the presence of free hydrated ferric oxide. There may be a certain amount of mechanical eluviation resulting in a certain differentiation into a light-textured A, and a heavier-textured B horizon. The granular or crumb structure of the surface soil is in contrast with the loose structure of the A horizon in podsoles.

It should be added that all gradations are possible from podsoles to brown earths.

The following appear to be essential characters of the great world group of which the brown earths or brown forest soils found in different parts of the world are variants.

(1) The profile is completely leached of carbonates. Carbonates may be present in the C horizon, or in the top soil as residues from added dressings. Drainage is free.

(2) The colloidal complex is not highly base-saturated and the reaction is only moderately acid.

(3) The humus is of the "mild" type, well distributed throughout the upper horizons without any tendency towards the development of a peaty layer.

(4) The composition of the clay complex in soils of primary weathering tends towards a  $\text{SiO}_2/\text{R}_2\text{O}_3$  ratio of 2.0, representing a stage in desilicification intermediate between that of the chernozem group and that of the lateritic soils of the tropics.

(5) Free sesquioxides are present, and the hydrated ferric oxide thus occurring gives a brownish or reddish-brown colour, which may be masked by humus.

(6) There is no differential eluviation of silica or sesquioxides and the  $\text{SiO}_2/\text{R}_2\text{O}_3$  ratio of the clay remains fairly constant down the profile.

(7) The soil structure is moderately granular.

(8) The natural vegetation is deciduous woodland or scrub.

W. M. Davies and G. Owen give the following description of a brown earth in Shropshire (England).

0-9 in. Brownish-reddish, loamy sand. Crumbly and somewhat gravelly.

9-18 in. Similar material, but rather more compact. Gravelly.

Below 18 in. Disintegrated lavender sandstone, passing into a layer of purplish-red marl at 40 in.

The principal analytical figures are shown in Table 37.

TABLE 37

*Analytical Data for Shropshire Brown Earth  
(Davies and Owen)*

Depth	0-9 in.	9-18 in.	Below 18 in.
pH ... ..	4.77	5.10	5.34
Clay % ... ..	16.3	17.50	15.30
Ignition loss % ... ..	4.95	3.28	3.00
Clay, $\text{SiO}_2/\text{Al}_2\text{O}_3$ ... ..	2.44	2.48	2.54
„ $\text{SiO}_2/\text{R}_2\text{O}_3$ ... ..	2.06	2.04	2.07
„ $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$ ... ..	5.42	4.86	4.40

The profile is somewhat more acid than is usual in brown earths. The constancy in composition of the clay fraction should be noted.

No figures for organic carbon are given, but the ignition loss suggests low figures.

W. G. Ogg gave the following analytical data for a brown earth in Aberdeenshire (Scotland).

TABLE 38  
*Aberdeenshire.—Cultivated brown earth over Gabbro (W. G. Ogg)*

Layer ... ..	(1)	(2)	(3) A	(3) B	(3) C	(4)
Depth in Cm....	0-25	25-35	50-60	70-85	90-100	130-140
pH ... ..	5.1	5.6	5.7	5.7	5.6	5.8
Loss on Ignition ...	14.9	8.6	4.4	4.8	4.1	2.7
Exchangeable Ca (M. eq.) ... ..	6.6	3.4	4.3	14.1	10.4	10.8
Exchangeable Mg (M. eq.) ... ..	0.5	0.3	0.4	4.7	2.7	2.4
Exchangeable H (M. eq.) ... ..	11.9	8.4	2.3	2.6	1.8	1.3
Clay per cent....	20.9	11.2	12.9	14.3	4.8	4.1
Clay fraction :						
SiO <sub>2</sub> /R <sub>2</sub> O <sub>3</sub> ... ..	1.19	1.11	1.48	1.74	1.57	1.64
SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub> ... ..	1.63	1.46	1.93	2.41	2.13	2.23
Al <sub>2</sub> O <sub>3</sub> /Fe <sub>2</sub> O <sub>3</sub> ...	2.72	3.17	3.27	2.60	2.81	2.76

The brown earths include a great variety of well-drained to moderately well-drained soils occurring in the temperate humid regions ; they are common in Great Britain, Western Europe, the Eastern United States, etc.

They may occur in Continental Europe as far north as southern Sweden. As in the case of the podsols, parent material plays an important part. Thus, whilst the typical well-drained soils of southern and eastern England are brown earths, where the parent material is quartzose sand, poor in basic materials, podsols are developed. On the other hand, with basic parent materials, brown earths may occur even in such a cool climate as that of Iceland. There are, however, differences between brown earths of high and mid-latitudes. With increase in mean annual temperature, oxidation of plant residues becomes more intense and the organic matter status tends to fall. The colour of the mineral portion of the soil also tends to become lighter and more vivid.

Agriculturally the brown earths are considerably better than the podsols. Under ordinary farming conditions the incorporation of organic matter with the soil by the addition of farmyard manure and

by the cultivation of artificial grass leys, and the maintenance of the base-status by chalking, liming, or marling, have tended to modify the original brown earth soil and produce a type of soil which in some respects resembles the prairie soils.

Where the natural deciduous forest is removed and the soil is afforested with conifers, it may happen that deterioration in base-status proceeds to such a degree as to result in incipient podsolization. Podsolization is a deteriorative change, and it is important to realize that, on light soils under heavy rainfalls, the change from brown earth to podsol may easily follow the removal of deciduous forest.

### (3) PRAIRIE SOILS

The typical Prairie soils have developed in cool, moderately humid climates under the influence of a grass vegetation. The profiles are characterized by dark-brown to nearly black, mildly acid surface soils underlain by brown well-oxidized subsoils. The parent materials have a wide range in composition especially in their content of lime. The Prairie soils differ from those of the Chernozem group in having lighter colour of the surface soil and in the absence of a zone of lime accumulated by soil-forming processes.

The "prairie" soil of North America were long considered as identical with the Russian chernozems. During the excursion following the First International Soil Science Congress held at Washington in 1927, however, it was almost unanimously agreed that these soils, although originally steppe soils, only to a very slight extent presented the same characteristics as true chernozems. Most of them must have come into existence under conditions somewhat more humid than the chernozems, though they cannot have been quite so humid as those governing the formation of degraded chernozems or slightly podsollic grey and brown forest soils. This hypothesis is supported also by the geographical distribution of the prairie soils given in Marbut's map. Marbut treats the prairie soils as a separate group, because they are so entirely different from those of any other great groups that, for the present, it seems very unwise to attempt to include them in any of the established groups. The prairie soils are grassland soils, but were developed under a high rainfall. In this respect they seem to be unique, not occurring elsewhere in the world except possibly in small areas.

In illustration of the chemical characteristics of prairie soils Jenny gives Rost's analyses, which shows the composition of the profile of a prairie soil from the village Rice in Minnesota. Stremme uses the same data for the characterization of prairie soils, calculating the figures to a carbonate-free soil less the loss on ignition. These figures are given in Table 39.

TABLE 39

Depth of Horizon in cm.	Percentage of the Constituents in dry soil				Percentage calculated to carbonate and humus-free soil			
	2·5-15	18-30	33-61	63-91	2·5-15	18-30	33-61	63-91
SiO <sub>2</sub> ...	72·89	73·62	75·24	73·65	80·42	79·86	79·68	77·80
Al <sub>2</sub> O <sub>3</sub> ...	10·46	10·87	11·35	12·13	11·52	11·79	12·01	12·81
Fe <sub>2</sub> O <sub>3</sub> ...	2·99	3·21	3·42	3·81	3·30	3·48	3·62	4·02
MgO ...	0·72	0·74	0·88	1·21	0·80	0·80	0·93	1·28
CaO ...	1·24	1·81	1·24	2·08	1·25	1·21	1·13	0·77
Na <sub>2</sub> O ...	1·39	1·35	1·33	1·31	1·53	1·46	1·41	1·38
K <sub>2</sub> O ...	1·66	1·74	1·86	1·87	1·83	1·89	1·97	1·97
TiO <sub>2</sub> ...	0·50	0·52	0·54	0·53	0·55	0·57	0·57	0·56
P <sub>2</sub> O <sub>5</sub> ...	0·18	0·17	0·14	0·11	0·20	0·18	0·15	0·12
CO <sub>2</sub> ...	0·07	0·05	0·13	1·06	—	—	—	—
Loss on ignition ...	9·38	7·80	5·34	2·99	—	—	—	—
Total ...	101·48	101·25	101·47	100·75	101·40	101·24	101·47	100·71

It will be seen from the above figures that as we proceed downwards there is a gradual decrease in the amounts of SiO<sub>2</sub>, CaO, Na<sub>2</sub>O and P<sub>2</sub>O<sub>5</sub>, accompanied by a corresponding increase in the amounts of Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, MgO, K<sub>2</sub>O, and CO<sub>2</sub>. According to the data given by Truog, the soil is slightly or moderately acid.

For prairie soil (Marshall silty loam) Bradfield has obtained the values in addition to the pH as shown in Table 40.

These soils are therefore slightly unsaturated. The clay content increases with the depth.

Prairie soils in general belong to the category of clay or heavy loam soils, due partly to the humidity conditions favouring the chemical decomposition of minerals and partly to the formation of a sufficient amount of organic matter thoroughly mixed with the mineral part, as in the case of chernozems. The difference in structure which distinguishes these soils somewhat from normal

chernozems is probably to be attributed to the slight unsaturation of the absorbing complex.

The prairie soils resemble the chernozems in their organic matter profile. The abundant and deep rooted grass vegetation, the presence of a rich soil fauna, and, in spite of the leaching of calcium carbonate, the favourable base-status, all result in a deep enrichment of the soil in dark-coloured base-saturated organic matter.

TABLE 40

Depth of horizon ...	0-45 cm.	45-75 cm.	75-120 cm.	120-150 cm.
Total exchangeable bases ...	16.6	16.9	17.5	26.0
Exchangeable hydrogen ...	6.54	7.81	8.29	6.48
Absorption capacity... ..	23.1	24.7	25.8	32.5
pH value ... ..	6.31	5.67	5.55	6.33
N ... ..	0.176%	0.135%	0.078%	0.044%
Sand ... ..	0.3%	0.2%	0.6%	0.5%
Silt ... ..	74%	70%	67%	69%
Clay ... ..	24%	30%	32%	30%

Eluviation of sesquioxides and deposition in a B horizon does not occur. It may be conjectured that the clay complex in prairie soils has scarcely suffered to any appreciable extent that degradation into free silicic acid and sesquioxides which Stebutt postulates for the brown earths.

The following profile, developed on loess in Houston Co., Minnesota, is described by A. L. Gray.

- 0-9 in. Very dark greyish-brown mellow silt loam, nearly black when moist. Granular throughout and laminated. Grey specks in upper 5-6 inches, more noticeable in lower 3-4 inches.
- 9-19 in. Greyish-brown very granular silt loam. Granules larger than in first layer. Laminated granules noticeably grey coated.
- 19-30 in. Light brown silt loam with large aggregates, tending to blocky structure, slight lamination in upper 1-2 inches. Grey coatings on aggregates. Some organic material on surface of aggregates.
- 30-49 in. Parent material with transitional layer in top 6 inches. Yellowish-brown silt loam with no noticeable structure. Some light grey mottling in lower 8-9 inches.

Prairie soils doubtless occur in many parts of the world on the humid side of the boundary between the humid and arid soils. Economically, they must rank among the most fertile of the great groups, and their recognition and definition is an important task for the future.

There is a class of soils occurring in the humid west of Britain which may be considered to have some affinities with the prairie soils. These are the soils of permanent grass lands. The resemblance consists in their high content of organic matter well distributed throughout the soil profile. But inasmuch as, except on calcareous soils, their base-status is low, the type of organic matter formed by micro-biological decompositions will be greatly different, being of a less marked black colour. Further, the clay complex under such conditions is less stable than in the prairie soils.

#### (4) DEGRADED CHERNOZEMS

If the grass vegetation is replaced by coniferous forests the leaching becomes intensified and the chernozems loses some of its characteristics and become more like a brown earth or a podsol. The soils thus formed are called Degraded Chernozems.

The Russian workers have recognized a number of stages in the degradation of chernozems, ranging from the unchanged chernozem to definite podsolic forest soils with markedly bleached horizons below the forest litter.

#### (5) LATERITE SOILS

The term "laterite" was first used (1807) by Buchanan, who gave this name to the brick-coloured earth occurring in India suitable for making air-dried bricks. Since then a very rich literature dealing with laterites has been produced, due not only to the extremely interesting character of these formations, but also to their being the most characteristic formations of the tropics. Here, colour has failed to prove a trustworthy guide. For, some red earths resemble laterites, while there are laterites which are not red. The red colour of laterites is due to their  $\text{Fe}_2\text{O}_3$  content; but the formation of laterites is characterized by the fact that during the weathering of the silicates the  $\text{SiO}_2$  is almost entirely—in some cases completely—leached out, while the sesquioxides remain and some-

times are actually accumulated from elsewhere. Where the parent rock contained, in addition to  $\text{Al}_2\text{O}_3$ , also iron compounds, the soil formed takes on a red colour ; but where there was originally scarcely any iron in the parent rock, the soil formed is not red, but has a greyish colour resembling that of bauxite. Some scientists call these soils "bauxite-laterites."

Laterisation is not confined to the upper horizons but, as a consequence of the excessive warmth and abundant rainfall of the tropics, influences the transformation of the parent rock to a considerable depth, extending in many places to 50-60 metres. Immediately above the parent rock there is formed a lateritic layer which, while it retains the structure of the original minerals, is found to contain only sesquioxides unaccompanied by silicic acid. Sometimes we find above the accumulation zone an iron-ore zone, which in many cases is rich enough to be worth mining.

Laterite is defined as a concretionary mass of iron and other sesquioxides, formed as the illuvial horizon during the later stages of soil formation. The position and formation of this illuvial horizon are determined by the ground-water regime rather than by the climate which must, however, be sufficiently moist to support forest growth.

The characteristic properties of laterites are as follows :—

(1) Considerable depth and freedom from iron pans, stones, or gravel—except that a few large stones may occur, but these are usually encrusted with ferric oxide.

(2) The soils are usually red, though the colour may vary from yellow to dark brown.

(3) They are fairly uniform in composition throughout their depth, and they contain much free ferric or aluminium oxide or both : their  $\text{SiO}_2/\text{R}_2\text{O}_3$  ratio is lower than in any other soil.

(4) They show certain cultivation and ecological characteristics.

From the circumstances that laterites occur commonly in the tropics it was at first supposed that laterisation is in some way a purely tropical process requiring drainage water to dissolve the silica. But it is now known that most tropical forests, under which laterite is often found, give acid humic layers and yield acid percolating water : laterites and lateritic soils have been found outside the tropics, and given suitable parent material, freedom from disturbance for a sufficient length of time, and free drainage to allow of sufficient leaching away of the silica there seems no need

to involve special reactions to account for the formation of laterites. Goldschmidt has described a laterisation of Norwegian labradorite under semi-Arctic conditions. Weathering somewhat resembling laterisation has been observed in Scotland, and elsewhere in non-tropical conditions. An essential condition is freedom from disturbances for periods long enough to enable the processes to complete themselves. This condition is more commonly obtained in the wet tropics, where the combined heat and moisture accelerate the weathering, than in dry or cold regions.

Mohr showed that true laterites occur in Java only where humus oxidises so rapidly as to eliminate the possibility of solution of the sesquioxides by organic acid. When the vegetation cover is denser the humic acid persists longer and podsolization takes place.

**Chemical Characteristics.** What has been said above makes it necessary to divide the dynamic phenomena prevailing in common laterites into two groups—the stages of leaching and of accumulation respectively. During the wet and hot season there is a prevalence of silicate weathering and of leaching down. This leads to an almost complete removal of bases generally and to so intensive a leaching of silica that the  $\text{SiO}_2 : \text{Al}_2\text{O}_3$  ratio sinks far below 2. In dry periods, under the protection of the humus or  $\text{SiO}_2$  sols, in a slightly acid medium (rich in  $\text{CO}_2$ ) the sesquioxides migrate upwards and if they reach the surface precipitate and accumulate as a ferroginous crust. This accumulation may be on such a scale that all plants die off and the soil becomes transformed into a dead rock.

Laterites in general are rich in colloids. According to Bennett there is on the average 72.7 per cent. of colloids in the clayey tropical soils in Central America. True laterites are, however, not plastic, being easily friable in a dry state. This is attributable to the large quantities of hydrargillite ( $\text{Al}_2\text{O}_3 : 3\text{H}_2\text{O}$ ) in well-developed laterites, which reduces the plasticity of the colloids. Of the mechanical composition of laterites we may in general say that they possess a very fine dispersivity and, as the colloids are unsaturated, they are very inclined to disperse in water, while when dried they crack deeply.

**Morphological Characteristics.** In a fully developed laterite profile we can distinguish four horizons :

- (1) the lowest horizon, composed of the original parent rock frequently 50-60 metres below the surface ;
- (2) on this, and formed from it rests the horizon of decompo-

sition, which in the present main type is lateritic and contains  $\text{Al}_2\text{O}_3$  in the form of a hydrate ;

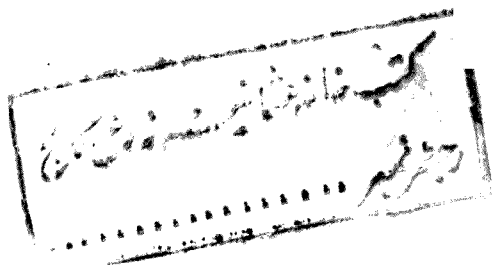
(3) above (2)—but actually formed from it—lies the accumulation horizon, which is red loam and mottled as a result of the accumulation of  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$  ;

(4) finally, the surface iron horizon (crust) formed from (3) as an efflorescence, below which we not infrequently find an alumina gel layer.

The higher the development of a laterite, the less its suitability—owing to the intense leaching—for vegetation. The well-developed laterites are therefore bare, the density of the vegetation being in inverse proportion of the development of the iron crust.

Laterite is regarded as a sub-soil formation produced by the weathering of basic rocks under alternate wet and dry tropical conditions. It occurs on the surface only when this is exposed by erosion. The overlying, usually red, soil is the product of disintegration and decomposition of laterite. The fertility of laterite is largely a function of its water-holding capacity. When underlying a thick soil layer it is usually a favourable medium for root growth.

Red soils rapidly absorb all phosphates applied by the ordinary methods which diminish the contact between the phosphate and the soil. The application of phosphates in the form of briquettes or in granular form was found to be successful.



*The Great Hydromorphous Soil Groups of the  
World and their Development*

THESE soils are distributed far and wide all over the world. They are very common in the arctic regions and are also encountered in temperate and sub-tropical countries.

Impeded leaching and lack of free percolation is the keynote of the development of this world group of soils. They may be schematically shown as in Table 41.

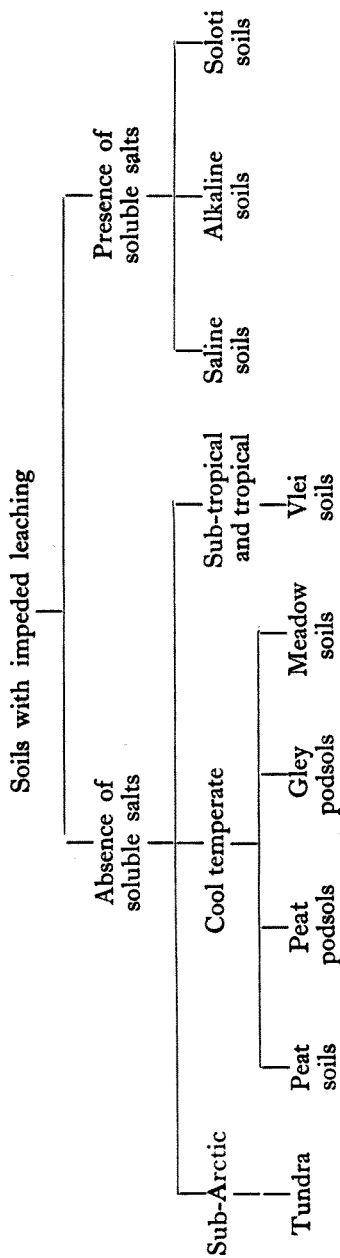
(1) TUNDRA SOILS

The term "Tundra" is used generally to denote the flat, treeless, more or less frozen regions of the arctic zones that have a covering of snow which only disappears in the warmer summer months. The only vegetation found there is scanty, consisting of mosses and lichens. Very large tracts of land of this kind are found in particular in North and North-East Russia. According to estimates made by Praslov, the tundra zone in European Russia alone occupies an area close of 243,000 square kilometers. Its area in Siberia is many times greater than that.

In the tundra region, the dominant factors in soil formation are physical weathering and waterlogging. The latter is occasioned by the scanty evaporation, which results in the prevalence of a humid climate even where the rainfall is comparatively small. Chemical weathering and micro-biological activity are naturally less pronounced than in warmer climates, but are not entirely suppressed.

Tundra soils result mainly from physical weathering and are consequently poor in clay. They exhibit a natural tendency to peat formation. The peat horizon is often dissected by running water into a characteristic hummocky formation.

TABLE 41  
HYDROMORPHOUS SOILS



The occurrence of a perpetually frozen subsoil in the tundra region has been discussed by C. Nikiforov. Whilst the prevalence of a mean annual temperature below freezing point might sufficiently account for the existence of a permanently frozen layer, it has been held by some investigators that this phenomenon is a survival from the Glacial Period. Perpetually frozen subsoils occur outside the tundra region and may sometimes underlie the more northern podsoils, black earths, and chestnut earths.

In describing the soils over the vast area of perpetual freezing, Nikiforov points out that the rapidity with which the soils thaw during the summer depends upon their texture and the character of the protecting vegetation. During the warmer portion of the year, therefore, the upper surface of the frozen layer is very uneven. The water cannot percolate through it, because the first water reaching it seals with ice all cracks in the frozen subsoil. All water derived from rain and snow and the thawing of the subsoil accumulates above the ever-frozen layer, often in such quantities as to form a liquid layer under the dry thawed surface. Such a condition favours the extensive development of swamps not only in the lowlands but upon the mountain slopes as well.

Sukachev describes a profile cut of soil in the tundra region between the rivers Kara and the Lower Ob as follows :

A<sub>0</sub> : 3 cm. deep. The humus accumulation layer, greyish-brown, the plant materials in places being only slightly decomposed.

A<sub>1</sub> : 2 to 3 cm. deep. Yellowish-brown, in places greyish brown, ochereous loose loam.

A<sub>2</sub> : 8 to 10 cm. deep. Dark bluish-grey homogeneous sticky viscous loam ; flowing when dug out, liquid-like when in a monolithic box. There is a sharp line of separation between this and the overlying horizon.

B<sub>1</sub> : 2 to 3 cm. deep. Brownish-yellow (ochereous) loam, similar to A<sub>1</sub> but more compact.

B<sub>2</sub> : 25 to 30 cm. deep. Compact, dark brownish-grey loam ; in the lower portion of this horizon black spots (humus) and rock fragments are found ; at a depth of 79 cm. below the surface the frozen subsoil is struck, but still the character of the described horizon does not change even deeper.

Tundra soils are capable of furnishing grazing for large numbers of reindeer, and some move to utilize it for this purpose has started.

## (2) MEADOW OR GLEY SOILS

These soils, which have certain affinities with the podsols and occur under similar climatic conditions, owe their distinctive characters to the presence of a ground-water table at or near the surface. At this level, a characteristic horizon, known as a gley horizon, is developed. This is distinguished by the deposition of rusty streaks and mottlings of hydrated ferric oxide. The deposition of hydrated ferric oxide in the gley horizon may attain considerable proportions and form the well-known lake ore or bog iron-ore. Deposition of manganeous and calcareous material may also occur, whilst there is frequently an enrichment in clay. The sub-aqueous horizons are generally grey, often with a bluish tinge, owing to the presence of vivianite. The surface horizon is grey and carries a peaty layer.

Ground-water soils occur throughout middle, northern, and western Europe, and indeed, throughout all the humid regions. In Europe, they attain their greatest development in the Pripet march region of Poland. Analogous conditions in more arid regions may give rise to saline and alkaline soils.

These soils are essentially local in character, and depend, in the main, on topographical conditions which influence the movement of underground water. Most typically they are developed in hollows, but where drainage is impeded by impervious strata on slopes, the typical characters of the gley profile may also be developed.

These gley soils are common in depressions in regions of podsollic soils. In passing from an upland to the bottom of a depression in such regions, a regular succession of profiles can frequently be observed. In the upland, with free drainage and scanty accumulation of peaty organic matter, iron podsols may occur. In the moister lower levels, the humic layer becomes thicker, and gley podsols and peat podsols result. In still lower ground, the water-table is sufficiently near the surface to give the gley horizon characteristic of a meadow profile, which gives place in turn to a peat profile. Gley podsols may result through impedance on the development of ortsein in podsol profiles.

The principal analytical data are given in Table 42.

The gley horizon is sometimes blue-grey mottled with large red spots and veins, and sometimes it is mottled reddish or rusty with blue-grey spots and veins. This horizon is very common in the

deeper layers of profiles of heavy soils. G. W. Robinson has given a typical analysis of a weakly gleyed ground-water soil under grass and compared it with a better drained and somewhat higher-lying brown earth on the same farm (Table 43).

TABLE 42  
*Analytical Data for Scottish Gley Soil*

Depth (in cm.)	0-5	5-15	15-22	22-35	35-55	55
pH ... ..	5.2	5.3	5.6	5.4	5.8	5.5
Ignition loss ... ..	18.4	12.6	7.3	5.2	4.1	3.6
Clay SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub> ... ..	2.96	2.85	2.98	2.89	2.79	2.29
„ SiO <sub>2</sub> /R <sub>2</sub> O <sub>3</sub> ... ..	2.44	2.32	2.37	2.28	2.12	1.82
„ Al <sub>2</sub> O <sub>3</sub> /Fe <sub>2</sub> O <sub>3</sub> ... ..	4.69	4.38	3.89	3.74	2.41	3.87

TABLE 43  
*Analyses of Ground-Water Soils as Compared with the Better Drained Brown Earth*  
(G. W. Robinson.)

	Ground-Water Soil			Brown Earth			
	0-10 in. Greyish Loam	10-20 in. Greyish Brown Mica- ceous Loam	20-30 in. Grey and Brown Mottled Mica- ceous Heavy Loam	0-9 in. Dark Brown Stony Loam	9-15 in. Brown Stony Loam	15-36 in. Reddish Brown Stony Loam	36-48 in. Yellow- ish Brown Stony Loam
Organic Carbon per cent. ...	3.6	0.8	1.4	2.90	2.05	1.10	0.0
Clay per cent.	20.7	15.7	14.3	18.7	20.0	16.9	—
pH ... ..	6.9	8.0	8.0	5.4	5.6	5.9	5.8
Clay fraction:							
SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	2.50	2.63	2.66	2.39	2.47	2.41	2.64
SiO <sub>2</sub> /R <sub>2</sub> O <sub>3</sub> ...	2.05	1.99	2.02	1.80	1.85	1.80	2.05
Al <sub>2</sub> O <sub>3</sub> /Fe <sub>2</sub> O <sub>3</sub>	—	4.53	3.11	3.15	3.05	2.99	2.95

**General Characteristics of Meadow or Gley Soils.** The common characters which distinguish these soils are greyish to black surface horizons sharply defined from the sub-surface horizons, which, by their iron stains, mottlings, or concretions, and also, in many cases, by the presence of gypseous or calcareous horizons, give evidence of the alternation of aerobic and anaerobic conditions due

to variable ground-water levels. The deposition of hydrated ferric oxide may often reach notable proportions, as in the soft bog iron-ore of northern lands and the harder "murrum" or "mocarrero" of the tropics.

Soils developed under conditions of impeded drainage may, in some cases, show resemblance to the black earths. The relatively high content of organic matter often developed under neutral or alkaline conditions may result in a dark colour in the surface horizons. Further, the drainage impedence and the high base-status both tend to the development of a siliceous type of weathering complex analogous to that of the chernozem group. Finally, the presence of a ground-water table may in many cases be associated with the deposition of calcium carbonate in the adjacent horizons. Meadow soils are, however, distinguished from the chernozems by the absence of the granular structure and by the occurrence of rusty mottlings or streaks, indicating the alternation of oxidative and reductive conditions.

W. G. Ogg describes a gley soil developed on Silurian shale boulder clay in the Moorfoot Hills, Scotland. The altitude is 1,250 feet, the mean annual rainfall 35-40 in., and the vegetation *Juncus communis*.

- (1) 0-5 cm. Mat of roots and moss.
- (2) 5-15 cm. Brownish-grey silty loam ; wet ; no definite structure ; few stones ; roots common ; some brown patches along root-channels.
- (3) 15-22 cm. (Variable). Grey silty loam with brown patches and streaks ; wet ; few stones ; roots common ; brown staining along root-channels.
- (4) 22-35 cm. Brown silty loam with greyish tinge ; wet ; slightly gritty ; few stones ; much brown mottling and staining along root channels.
- (5) 35-55 cm. Greyish-brown silty loam with sandy patches ; wet stones common ; blackish particles or concretions ; roots penetrate ; brown staining along root-channels.

### (3) PEAT SOILS

There are vast areas of peat land in different parts of the world, and, although these deposits are most extensive in regions of moist

and temperate or cool climate, they also occur in the tropics and sub-tropics. In fact, peat formation may occur anywhere if the conditions are such that the decay of plant remains (and animal remains should they be present) is checked or prevented. Micro-organisms are chiefly responsible for the decay of organic matter, and there are several factors which may hinder or prevent their action. Probably the most important is the presence of an excessive amount of moisture, which excludes air ; hence peat formation is associated with waterlogged conditions. Other factors which are associated with the formation of certain kinds of peat are high acidity and a shortage or absence of the nutrients which the micro-organisms require.

There is an enormous amount of peat in the world and in some regions a large proportion of the land surface is peat-covered. In Europe there are said to be over 100 million acres of peat land. It has been calculated that the carbon content of the peat in the world is practically double the carbon content of the atmosphere, about three times the carbon content of all the organic matter in mineral soils, and nearly double the carbon content of all living matter.

Peat formation tends to occur in hollows or where the land surface is flat and poorly drained, but where the climate is sufficiently humid it may also occur on comparatively steep slopes. There are, therefore, many different varieties of peat, and the differences occur not only in different places but in the different layers of peat on one place. For example, peat may begin to form from sedge plants in a hollow where the drainage water is rich in plant food, but as the peat accumulates and the surface rises, a new type of vegetation may appear and this may give rise to a layer or layers of peat quite different from those below. An examination of a peat bank will frequently show several clearly marked layers, obviously derived from quite different types of plants. These differences may also be due to differences of climate which have occurred throughout the ages.

Peat deposits may reach to a depth of 50 feet or even more. The rate of accumulation has been variously estimated. Whilst the vertical rise of the surface may amount to 1.2 cm. per annum, the actual growth of solid peat must be considerably less. According to Bersch the rate of accumulation in some parts of Wales is about 9.7 mm. per annum.

W. Bersch gives the following typical example :—

- (1) Vegetation layer.
- (2) Younger moss peat, 140 cm.
- (3) Light coloured transition layer (heath), 20 cm.
- (4) Older moss peat, 170 cm.
- (5) Woody peat, 85 cm.
- (6) Fen peat, 70 cm.
- (7) Peat mud, 15 cm.
- (8) Mineral horizons.

Horizons 1 to 4 represent the high-level peat or the high moor peat or the mosspeat ; horizon 5, the transition (woodland) stage ; and horizons 6 and 7, the fen peat, or the low moor peat. The transition layer between the older and the newer peat moss is generally considered to represent a period of relatively dry conditions involving an intermission of sphagnum peat formation, and the establishment of heath.

**Properties of Peats.** Since peat is due to the accumulation of plant remains, it follows that a pure peat is composed mainly of organic matter. There is, of course, a small amount of mineral matter derived from the plants which form the peat, and some mineral matter may be blown or washed in while the peat is being formed. Associated with their organic nature, peats have a very high water-holding capacity. Wet peat can hold as much as 95 per cent. of water and even well-drained peat land contains about 85 per cent.

Peats differ widely in physical texture and chemical composition in consequence of the different kinds of plants from which they are formed, and the different conditions under which they have developed. Some are fibrous and the plant tissues show little decomposition, whilst others are slimy and colloidal and exhibit little or no trace of firm plant structure. When a piece of wet fibrous peat, e.g. fresh sphagnum peat, is squeezed in the hand, water runs from it as from a sponge, whilst a handful of the other extreme type, e.g. *Scirpus* peat, squelches through the fingers like porridge and little or no water is pressed out. This difference has an important bearing on the horticultural uses of peats, as the highly decomposed types do not re-wet readily after drying.

On the chemical side there are equally important differences. Fen types are much less acid than moss types. They not only contain much more lime but they are richer in nitrogen, phosphoric acid and

potash. On account of this greater natural fertility, Fen types have been cultivated far more extensively than moss types. With suitable treatment, however, even the moss types can be rendered highly productive, but at a greater cost. Peats are much richer in nitrogen than mineral soils, but only a small amount of this is available until the biological and chemical processes are set up which bring about the decomposition of the protein residues. Hence crops in freshly reclaimed peat land may suffer from nitrogen starvation although large reserves of nitrogen are present. This applies to moss types of peat.

The biological conditions in peat land are very important. Under natural conditions, there is little or no bacterial activity in peats because of their water-logged condition, and, in moss types, high acidity and a shortage of nutrients. Bacterial activity is stimulated by draining, cultivation, liming and manuring; the application of farmyard manure is highly beneficial as it not only supplies nutrients, but also introduces large numbers of bacteria into the more or less sterile peat. Satisfactory humification of peat land does not take place until a good vigorous bacterial population has been established. Since nodule bacteria are often absent in uncultivated peat land, it is generally desirable to inoculate the seeds of legumes before sowing on freshly reclaimed peat land.

**Mineral Contents of Peats.** The amounts of inorganic substances in peats are very small compared with those of organic matter. The amount and composition vary considerably and depend on the composition of the plants from which the peats were formed, and on the conditions under which they were formed. The plants which go to form the moorland or moss types, have a very low content of minerals and the water associated with the formation of these types is also low in mineral salts. The plants which form lowmoor peats have a higher mineral content, the water is richer in minerals, and they are usually less carried away in solution. Consequently, the lowmoor types are richer in mineral matter, especially in calcium, than the moorland or moss types. This has a very important bearing on the natural fertility of peat land and has led to the lowmoor types being developed far more extensively than the moorland types for agricultural purposes.

**Agricultural and Horticultural Uses.** Peat is used for many purposes in connexion with agriculture and horticulture. It is employed as a packing material for fruit and vegetables, and it is

used in a whole variety of forms as a manure. It is useful as stable litter, as it readily absorbs liquid manure ; the nitrogen of the peat also gradually becomes available as the organic manure. For stable litter sphagnum and other fibrous types are most suitable. Raw peat is now used fairly extensively in horticultural work as a mulch and as a source of organic matter. In order to assist decomposition, and to increase its value as a manure it is often composted with other materials. A considerable amount of attention has been given in recent years to the study of growth-promoting substances or auxinones, and attempts have been made to prepare from peat manures containing these substances. Attempts have also been made to introduce suitable bacteria into soils through the medium of bacterized peat. Peat is also used in some compound chemical fertilizers, and in some stock foods.

**Reclamation of Peat Soils.** Peat land can be developed for agricultural purposes, and large areas of fen peat have been brought under cultivation. Fen peat is much less acid than moorland peat—in fact some of it is not acid at all—and contains considerable reserves of lime and other substances necessary for the growth of agricultural plants. One of the lines of research being carried out at the Maculay Institute in Scotland, is on the improvement of the poorer classes of land including moorland. In dealing with deep moorland peat it was at one time considered necessary to remove most of it and replace the surface turf on what remained. This was then incorporated with the underlying mineral soil by means of cultivation implements. This plan was economically possible when peat was used more extensively as fuel, but most of the recent reclamation work has been carried out on the surface of the peat without removing any of it, and excellent results have been obtained.

Two large-scale reclamation experiments on peat of the moorland or moss types most common in Scotland have been carried out by the Maculay Institute.

The system of reclamation is as follows : The land is, first of all, drained and the details of this depend on the particular conditions. Collecting ditches 5 ft. deep and 3 ft. wide at the bottom have been dug at intervals of 300 yards. These discharge into an existing stream and are to be left open. Subsidiary ditches 4 ft. deep have been cut at intervals of 20 yards and these discharge into the collecting ditches. In the subsidiary ditches, after shrinkage has taken place, wooden box drains are laid. These are constructed by nailing together

four boards (leaving suitable slots for water to enter) to give a channel about 4 in. square. The advantage in the use of the wooden box drain is that it gives one continuous channel the whole length of the drain, and this helps to obviate the displacement which is so apt to occur in peat. The cultivation of peat land also presents special problems for it is difficult to secure a good tilth, but a rotary cultivator, drawn by a tractor of the caterpillar type, has been found to give satisfactory cultivation at a low cost. Frequent rolling with a heavy roller is necessary on some types in order to compact the peat and keep moisture in the surface layer. The addition of lime is necessary where peats show a high degree of acidity and in this case a dressing of about 2 tons CaO per acre was applied. The amount of lime which should be applied varies with the peat and with the crop to be grown, but overliming has a very detrimental effect and must be avoided. The application of lime is followed by a great increase in the number and activity of bacteria and humification is promoted.

No hard and fast rules can be laid down regarding manuring, but moorland types are very deficient in phosphoric acid and potash, and require heavy dressings in the first few years after reclamation until reserves are built up. Attention should also be paid to possible deficiencies in minor plant foods. Farmyard manure and composts are particularly useful on newly reclaimed peat land for they stimulate bacterial activity as well as providing nutrients. Various crops have been grown successfully on newly reclaimed peat land. Hay and pasture seem to be particularly suitable but oats, silage, potatoes, and other vegetables have also been grown. In addition to full reclamation which is an expensive business, experiments have been carried out on the improvement of moorland for grazing. Where drainage is unnecessary worthless land can, by the addition of lime and suitable manures, be converted at a moderate cost into good clovery pasture.

According to Bakhulin, the yields of crops are not increased by the addition of phosphates if the content of  $P_2O_5$  in the peat is 0.5 per cent. The forms of phosphate fertilizers to be used are determined by the kind of peat, by the contents of Cu and mobile Al, exchange acidity and by the pH value.

Dokukin found that "Reclamation disease" attacks all plants grown on newly reclaimed peat soils except potatoes. This particular disease was treated with Cu-containing waste products.

## (4) VLEI SOILS

This Afrikaans word, pronounced "flay", may be conveniently used for the tropical and sub-tropical analogues of the meadow soils.

It has been given to certain African soils which occur in depressed or basin-shaped areas subject to seasonal wetness. They may be black, brown, or grey in colour and often show mottling due to the prevalence at certain seasons of waterlogged conditions. Ironstone concretions are frequently present, and calcium carbonate nodules are also encountered.

G. Milne describes a typical vlei soil in a saucer-shaped depression at Muhesa, Tanganyika. The altitude is 600 feet and the rainfall 50 inches with maximum in March-May and November-December. The original vegetation was tall dense grass. The profile is :—

0-4 in. Friable grey-black surface soil.

4-10 in. Inky black sticky subsoil.

Below 10 in. Mottled yellow soapy clay to 11 feet.

There are many ferruginous concretions through the subsoil and traces of calcium carbonate from 18 inches downwards. The following data for the Muhesa vlei soil were obtained in G. W. Robinson's laboratory at Bangor (N. Wales).

TABLE 44  
*Analytical Data for Muhesa Vlei Profile.*

Depth	Clay %	Organic Carbon %	pH	Clay Fraction		
				SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub> /R <sub>2</sub> O <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub> /Fe <sub>2</sub> O <sub>3</sub>
0-4 in.	27.6	2.99	7.6	2.99	2.47	1.62
4-8 in.	31.9	2.56	6.9	2.92	2.36	1.66
26-32 in.	45.4	0.85	6.3	2.15	1.79	5.00

## (5) ALLUVIAL SOILS

Alluvial soils occur in all parts of the world, on flood plains, or low terraces along streams. In some of the mountainous sections there are alluvial soils on the more recent alluvial fans or so-called colluvial slopes. The term "alluvial soils," however, applies only

to the more recently deposited water-laid materials, which have been very little changed by the environment. Their characteristics are determined largely by the nature of the materials from which they have been derived and the manner in which these materials have been sorted and deposited. The climatic conditions, drainage, and vegetation vary widely.

These soils show all stages of development according to their age. Where time has sufficed, development can occur on alluvial material just as on any other kind of parent material. It would therefore be incorrect to describe a podsol developed on alluvium as an alluvial soil. The term is best restricted to juvenile soils with undeveloped profiles in which the soil characters are dominated by the parent material.

Agriculturally, these soils are of considerable importance. They are found in most countries and are generally of high fertility. Examples are the delta soils of Egypt and the polder soils of Holland. In many cases the latter have been reclaimed from tidal water by means of dykes. A considerable proportion of Holland has been thus won from the sea. The soils of older reclamations have undergone considerable changes. In the early years there is a leaching out of soluble salts, followed by a gradual loss of calcium carbonate and fall in base status. With skilful management, including the regulation of water conditions by drainage, these soils are very productive. In England the fertile agricultural soils of S. Lincolnshire are of this class.

#### ✓ (6) SALINE SOILS

The saline soils are of very common occurrence in regions where alkali salts—in particular sodium salts—have accumulated. The accumulation of sodium salts is often accompanied by an accumulation of magnesium salts, and may be due to very different causes.

F. Harris enumerates a whole series of sources from which the salts of the various saline soils may accumulate. Scientific literature keeps continually suggesting other possibilities. If we desire to establish something like a system for these possibilities, we must divide the sources of the salts into four main groups—action of the ocean (oceanic), action of volcanoes (volcanic), weathering and decomposition of dead organic matter.

However, for the salts to accumulate in the soil it is not enough

that they should enter the soil or be formed in the soil, they must also be retained there. This may happen in several ways : (a) owing to the subsoil water table being continuously so high that the various sodium salts cannot be removed by natural drainage ; (b) owing to the impervious subsoil preventing leaching out of the sodium salts ; (c) owing to the evaporation of soil moisture being so rapid that the salts washed down by rain are brought to the surface again by capillarity ; (d) owing to various combinations of the above three factors.

**Dynamic Characteristics.** The dynamic character of saline soils is determined by those chemical, physical and biological phenomena which are dependent upon the qualitative and quantitative changes of the water-soluble alkali salts contained in the soils.

**Chemical Characteristics.** The chemical characteristics of saline soils are determined primarily by the chemical composition of the water-soluble salts.

The salts of littoral saline soils originally correspond to the proportionate quantities of sea-water salts. Clarke gives the following average composition of sea water :—

TABLE 45

NaCl	...	...	...	77.76 per cent.
MgCl <sub>2</sub>	...	...	...	10.88 " "
MgSO <sub>4</sub>	...	...	...	4.74 " "
CaSO <sub>4</sub>	...	...	...	3.60 " "
K <sub>2</sub> SO <sub>4</sub>	...	...	...	2.46 " "
MgBr <sub>2</sub>	...	...	...	0.22 " "
CaCO <sub>3</sub>	...	...	...	0.34 " "
Total	...	...	...	100.00 per cent.

The salt content of saline soils varies considerably. We may nevertheless say that the bulk of salts are sodium salts combined with a certain quantity of magnesium salts. The anions occurring most frequently are Cl, SO<sub>4</sub> and carbonates, nitrates occurring only exceptionally—usually in places where there is decomposition of organic matter. The carbonates are present partly as normal carbonates, partly as bicarbonates. In some cases the composition of the salts is very simple, in others very complex.

**Physical Characteristics.** The mechanical composition of saline soils may vary considerably—as is only natural when we consider the possibilities of formation. Sodium salts may, however,

exercise a considerable effect upon the texture of the soil. In this respect there is a considerable difference between the effect of alkali carbonates and the carbonate-free sodium salts ; for while the former increase the latter decrease the degree of dispersion of the soil.

The morphological features of saline soils may vary considerably ; for while on the one hand the original soils themselves may differ materially in their morphology, on the other hand the quality, quantity and even the vertical distribution of the salts can give rise to so many varieties that there can be no talk of general morphological characteristics. The morphology of a saline soil usually resembles that of the original soil or is entirely structureless. The most characteristic feature of these soils is the saline vegetation, which—though it may vary from place to place—within any given district shows a close connection with the salt content and salt quality of the soil.

A typical profile from the vicinity of Akmolinsk, Russia, is described by G. Tumin :—

- A<sub>1</sub>. 0-1 cm. Light grey salt crust with carbonates, passing to a dark grey looser structureless horizon. Gradual transition to A<sub>2</sub>.
- A<sub>2</sub>. Brown with grey streaks and mottlings. Weak carbonate reaction. Numerous small flecks of salt to 30 cm. From 30-45 cm., larger flecks.
- C. Light brown salt-bearing loam, containing carbonates.

The whole profile is moist and the saline ground-water is encountered at 110 cm.

## (7) ALKALI SOILS

The physical behaviour of alkali soils in general is very unsatisfactory alike for cultivation and for plant growth. When it rains, they very slowly take up water, and even after a heavy rain they become wet only to a depth of 1-2 mm., below which they are hard and dry. This is due to the considerable swelling of the colloids and to the resulting increase of volume, which closes all the pores and makes them impervious. This explains also why in the dry state the pore volume of alkali soils is less than their water capacity. The same cause is responsible for their being scarcely permeable. Another characteristic feature of these soils is that if we mix them

TABLE 46  
*The Salt Composition of Russian Solontshak (Glinka).*  
 (Water Extract)

Depth in cm.	Dry Residue	Loss on ignition	In-organic Residue	P <sub>2</sub> O <sub>5</sub>	CaO	MgO	K <sub>2</sub> O	Na <sub>2</sub> O	Alkalinity		SO <sub>4</sub>	Cl
									Na <sub>2</sub> CO <sub>3</sub>	NaHCO <sub>3</sub>		
Efflorescence	0.813	0.011	0.802	0.0020	0.0402	0.0013	0.0111	0.2997	0.0015	0.0565	0.430	0.0070
1-4	5.369	0.062	5.303	0.0056	0.1126	0.0078	0.0249	2.0938	0.0024	0.0419	2.948	0.0310
10-20	1.982	0.095	1.887	0.0020	0.1107	0.0343	0.0291	0.7378	0.0004	0.0259	0.543	0.5810
103-110	0.790	0.009	0.780	0.0012	0.0114	0.0079	0.0076	0.3576	0.0015	0.0341	0.334	0.2661
130-140	0.378	0.001	0.377	0.0016	0.0049	0.0055	0.0058	0.1887	0.0025	0.0372	0.815	0.1331

with a large amount of water, we get a turbid solution which does not become clear after six months. This is due to the sodium in the complex exercising a peptising colloidal effect, though formerly it was attributed to the influence of sodium.

Alkali soils offer the best illustrations of the close connection between the physical properties of a soil and the chemical composition of the absorbing complex. The characteristic structure of these soils is clearly connected with the physical and chemical properties. The surface horizon is usually crusty or foliated due to deflocculation with water and the gradual settling of silt. This effect, however, does not penetrate to any great depth, as the soil does not easily take up water. Below the surface horizon we usually find the hard accumulation horizon (B), which may be divided into several sub horizons.

**Chemical Characteristics.** Glinka has published the total chemical composition of a "solonetz" profile soil from the Government of Yeniseyk, together with the values calculated to the purely mineral part. His figures are shown in Table 47.

Glinka concluded that there had been an accumulation of  $\text{SiO}_2$  and a decrease of bases and sesquioxides in the upper horizons ( $A_1$  and  $A_2$ ). The bases and sesquioxides were found to have accumulated most particularly in horizons  $B_1$  and  $B_2$ .

The chemical composition of the hydrochloric extract of a typical "solonetz" soil and that of the absorbing complex can best be illustrated by giving the data for an alkali soil from the Hortobagy region (Hungary). The composition of the hydrochloric extract of the profile is given in Table 48.

The first thing shown by the above figures is that the insoluble residue decreases with depth. This corresponds on the whole to the decrease with depth of the total  $\text{SiO}_2$  of "solonetz" soils, as most of the part insoluble in hydrochloric acid is composed of quartz. It is, however, equally clear that the proportion of the soluble  $\text{SiO}_2$ —which originates principally from decomposed silicates—is least in the upper horizon and reaches its maximum in the B horizon, as do also the soluble  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$ . We see, then, that the sesquioxides and the soluble  $\text{SiO}_2$  have been washed down into the B horizon, partly as free oxides and silicic acid gels and partly as complex gels.

Of the bivalent and monovalent bases the CaO reaches its maximum in the  $C_2$  horizon, the MgO and  $\text{K}_2\text{O}$  in the  $B_3$  horizon, and

TABLE 47  
Solonetz Soil (after Glinka)

Horizon (Depth in Cm.)	Percentage in Air-Dry "Solonetz" soil (Total Analysis by Fusion)											
	CO <sub>2</sub>	H <sub>2</sub> O (105°C.)	Loss on Ignition	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	K <sub>2</sub> O	Na <sub>2</sub> O	N	Total
A <sub>1</sub> (0-3)	—	1.09	9.29	66.48	11.98	3.87	1.57	0.99	2.35	2.46	0.070	99.27
A <sub>2</sub> (15-21)	—	1.11	3.42	71.89	12.01	3.79	2.29	0.31	2.29	2.58	0.096	98.706
B <sub>1</sub> (21 29)	—	2.72	5.37	33.36	14.76	4.71	2.89	0.74	2.60	1.98	0.066	99.486
B <sub>2</sub> (32-41)	0.58	2.00	7.86	62.94	15.48	5.23	3.25	0.28	2.42	2.77	0.114	99.518

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TABLE 48

Percentage calculated to Soil dried at 105°C.								
Horizon	A	B <sub>1</sub>	B <sub>2</sub>	B <sub>3</sub>	C <sub>1</sub>	C <sub>2</sub>	C <sub>3</sub>	D
Na <sub>2</sub> O ...	0.90	2.32	3.00	1.96	0.78	0.81	0.67	0.89
K <sub>2</sub> O ...	0.36	0.43	0.55	0.70	0.27	0.29	0.26	0.29
CaO ...	0.63	0.77	1.09	0.69	10.26	16.00	14.53	14.40
MgO ...	0.27	0.70	0.67	1.65	1.42	0.23	0.24	0.35
MnO ...	—	—	—	—	0.02	0.98	1.04	0.78
Al <sub>2</sub> O <sub>3</sub> ...	3.60	5.77	8.15	8.33	6.65	6.63	8.95	8.25
Fe <sub>2</sub> O <sub>3</sub> ...	0.57	3.32	6.81	7.00	4.14	4.14	4.63	4.50
SO <sub>3</sub> ...	0.18	0.26	0.58	0.46	0.01	0.01	0.27	0.17
P <sub>2</sub> O <sub>5</sub> ...	0.21	0.13	0.12	0.20	0.15	0.15	0.05	0.04
CO <sub>2</sub> ...	—	—	—	—	7.20	7.20	10.62	10.45
Soluble SiO <sub>2</sub>	5.83	10.88	20.75	21.20	12.94	12.94	13.50	13.36
Loss on ignition ...	10.94	2.02	2.24	2.25	1.96	1.46	1.61	2.15
Insoluble residue ...	76.50	73.75	55.75	55.15	54.80	46.00	44.00	44.95
Total ...	99.95	100.35	99.71	99.59	100.60	100.60	100.37	100.59

the Na<sub>2</sub>O in the B<sub>2</sub> horizon, showing that all have alike been leached downwards. Of the acid residues the SO<sub>3</sub> reaches its maximum in the B<sub>2</sub> horizon, the P<sub>2</sub>O<sub>5</sub> in the A and the CO<sub>2</sub> in the C<sub>2</sub> horizon, where there is an accumulation of CaCO<sub>3</sub>. The SO<sub>3</sub> residue concentrated in the B<sub>2</sub> and B<sub>3</sub> horizons represents the gypsum accumulation horizon.

The most characteristic feature is, however, the quantity of exchangeable cations, the data relating to which will be found in Table 49 (same profile as in Table 48).

TABLE 49

mg. Equivalents of Exchangeable Cations in 10 Grammes Dry Soil					
Horizon	Ca	Mg	K	Na	Total (S)
A	6.2	5.5	1.2	7.7	20.6
B <sub>1</sub>	9.6	6.1	1.0	14.6	31.4
B <sub>2</sub>	10.3	7.3	0.9	23.8	42.3
B <sub>3</sub>	9.9	9.5	1.0	20.5	40.9
C <sub>1</sub>	14.4	8.8	1.8	14.6	39.6
C <sub>2</sub>	15.5	8.6	2.9	12.4	39.1
C <sub>3</sub>	16.1	8.0	2.4	14.0	40.5
D	15.9	8.4	2.0	12.8	39.1

An interesting description of a solonetz has been given by Lapham as follows:—

0-5 in. Dark dull reddish brown to light reddish brown sandy loam of somewhat coarse gritty texture, containing some fine gravel, friable, slightly granular. Barren areas between desert shrubs and other plants are frequently covered with well-developed desert pavement of water-worn pebbles, with some larger stone. The pebbles are covered on sides and upper surfaces with a characteristic desert varnish of bluish-black vitreous appearance. This horizon is leached of lime and is mildly acid.

5-12 in. Dark dull red to deep red or maroon coloured heavy tight plastic clay of typical solonetz structure. Columnar, the columns 1 to 3.5 inches in diameter, breaking straight across, rounded on top. The columnar fragments are much coated with dark colloidal staining and there is a light sprinkling of leached grey siliceous material in cracks and on surfaces of the soil aggregates. This horizon underlies the surface soil very abruptly, and is noncalcareous.

12-30 in. Rich brown to light brown clay or heavy clay loam, columnar, but columns are less well developed than in horizon above ; colloidal glazing is less pronounced and the material is less tight and impervious and is mildly calcareous and slightly mottled with lime in the lower part.

20-36 in. Similar to horizon above but of higher lime accumulation, compact and softly cemented, vesicular structure.

44-72 in. Light grey, gravelly loam, highly calcareous and with leases and layers of gravelly material firmly cemented by lime carbonate.

**Solonetz "hard pan" Horizon.** The result of repeated washing through of the upper horizons by sodium-salt solutions is that the degree of alkalization may be much higher than in the earlier phases. But even if this does not happen in each single case, the advance in the leaching of the sodium salts is accompanied by a corresponding increase in the dispersivity of the absorbing complex, while as a consequence of downward percolation of the colloidal solutions the B horizon becomes more and more impermeable. This is the origin of the so-called "hard-pan" horizon, the horizon, which is impervious alike to water and to air, separating the upper horizons of alkali profiles from the lower horizons. The downward movement of surface water is possible only through the cracks formed in dry periods, these cracks serving as channels for the washing down of a part of the upper leached greyish

horizon, which then mottles the cross section of the lower and darker horizons and covers the surfaces of the dried clods with a sugar-like coating.

**Magnesium Solonetz.** Recently Kelley and others have described soils with a "solonetz" structure in which the proportion of exchangeable sodium is negligible. These soils they call "magnesium-solonetz" soils. If used in this sense the term "solonetz" refers to the structure of the soil only and does not correspond to the original idea expressed by the Russian word.

**Solonetz-like Soils.** Russian soil scientists distinguish typical "solonetz" soils and "solonetz-like" soils, the latter having been formed from other soil types such as tshernozems or chestnut steppe soils. Glinka describes the latter as occurring in the neighbourhood of "solonetz" soils, differing from them only in their "solonetz" formation being less well developed. He distinguishes "solonetz-like" and "slightly solonetz-like" soils.

#### (8) THE SOLOD OR DEGRADED ALKALI SOILS

The last stage, when the solonetz has been exposed to prolonged leaching, is the solod of the Russians and is found, for example, in depressions of the ground where the water used to collect, or on the high river terraces which, being flood terraces just after the glacial periods, were solonchaks. The profile of a solod formed in the absence of calcium carbonate is very similar in external appearance to the podsol. The upper layer is dark coloured and foliated, the soil below is black and crumbly with many fine roots, still lower it becomes grey, then still lighter in colour as the silica deposit becomes more and more pronounced, its structure is nutty, very different from that of the solonetz. The lower depths are like those of the solonetz: first the brownish prismatic horizon with its characteristic cracks coated with humus, and, still lower, its horizons of calcium carbonate and calcium sulphate. In this process of solodization, the percolating water continues to remove sodium and other products of decomposition from the soil complex, replacing the exchangeable sodium by hydrogen, and depositing the products of decomposition lower down. Eventually the surface soil becomes acid, though the sub-soil is first neutral and still lower down alkaline. The characteristic feature of these soils is the large amount of alkali-soluble silica that occurs in the top horizon.

The dynamics of both sodium and hydrogen soils operate jointly in the dynamic phenomena of these soils. However, since the dispersing effect of absorbed Na cations is even greater than of H cations, these soils are dynamically more closely akin to the sodium than to the hydrogen soils.

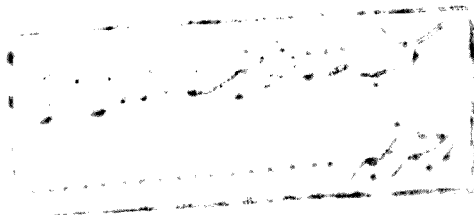
The essential difference as compared with alkali soils is that in the absorbing complex we find hydrogen penetrating at the cost of sodium. The reaction of the soil is acid.

A typical Russian soloti profile is described in the following terms by Korotky :—

- A<sub>0</sub>. Peaty layer with grass cover ; 3-5 cm.
- A<sub>1</sub>. Grey or ashen-grey layer with tongue-like projections from the peat layer ; 1-10 cm.
- A<sub>2</sub>. Whitish grey with numerous rust spots, and ferruginous concretions ; typical podsollic laminated structure ; 10-15 cm.
- B<sub>1</sub>. Brown varying to rusty or bluish-grey (humus) ; abundant humus mottlings ; a sticky clay ; numerous "orstein" grains in the upper portion, forming in the lower portion a black or dark brown material (iron and manganese compounds) ; on drying breaks into prismatic lumps.

The solods are more fertile than the solonetz soils since they do not possess the very impervious B horizon near the surface ; they therefore allow better and deeper root development in the upper horizons.

For full details of the evolution of alkaline and saline soils see Chapter 13.



*Analytical Soil Survey and Soil Productivity  
Ratings*

SOIL chemists and agriculturists frequently speak about soil "types", and yet the definition of the various types is a matter which presents very considerable difficulty. When soils that differ in some obvious respect are considered together, it is easy to refer to "this type" and "that type", and it is possible to ascertain in what particular respect the two soils differ. Nevertheless the mapping of soils in order to show the distribution of various types has proved to be an almost overwhelming problem on account of the difficulty of finding a satisfactory criterion of a soil type which will be of general application.

The general survey aims at recording the major types and showing how their distribution is related to the climatic, geological, topographical, vegetation, and other conditions over the area concerned. A soil map of Europe has been constructed by Professor Stremme, of Danzig, with the collaboration of many soil workers in different countries. An elaborate series of maps of the soil zones of Russia, America and Great Britain is being built up under the supervision of the leading soil scientists in these countries.

Whilst the aims of soil surveys are often mainly of an utilitarian character, work of this type is of great importance in elucidating the regional relationships of soils and the influence of climate and topography on soil genesis. Indeed, it is only by systematic mapping that the variations in soil characters within a region can be discovered and related together into a system, coherent in itself and capable of being inserted in a wider system.

Soil surveys have been in progress for many years in different countries, but the organization of soil survey work has been developed more thoroughly than elsewhere in the United States of America in the form of a national soil survey under the Federal Government. In other countries, surveys have been made by workers at provincial

institutions, or soil survey work has been included in the activities of the Geological Survey, as in Germany. In South Africa and Australia there are soil survey organizations especially devoted to irrigated and irrigable lands.

Whilst the survey of the soils of a new country should be carried out with careful attention to relationships with world groups, the first requisite is to obtain such a classification that the soils of the particular country will be thrown into the clearest possible relationship to each other. A valid classification of the soils of a given country is a necessary preliminary to their assignment to positions in a world system. It is, indeed, certain that fuller knowledge of hitherto unexplored soil regions will add materially to our list of soil groups.

As the Russian workers developed their soil science, soil mapping came more and more to be based upon soil characteristics and less and less on the environmental factors that produced them. In fact a soil map is a map of soil profiles. It would be useless, or almost useless, simply to map the texture of the surface soil, producing thereby a map showing the occurrence and distribution of clays, loams, sands, etc.

Surveying on the basis of the soil profile has two important characteristics :—

(1) It considers the soil as a whole. It is frequently said, referring to a particular area, that the soil has a certain mechanical composition, which statement implies that the mechanical analysis of the soil is uniform throughout its depth. Except in the case of certain new warp soils, this is probably never true. The study of the profile differentiates between the texture factors of different horizons. The same consideration applies to any other characteristic which may be studied separately in each horizon.

(2) It takes cognizance of the soil formation processes. The processes going on in a soil effect removals, leachings and depositions and the soil profile reflects these processes. The importance of this cannot be exaggerated, for it is a philosophical necessity that one cannot claim a scientific knowledge of soil without a knowledge and understanding of what has gone on in its formation, and what is still going on within it. Until recently there was too great a tendency to consider the soil statically, and to try and visualize its constitution as a fixed thing.

The features of the soil profile necessary to the definition of a soil unit are :—

- (1) Surface features.
- (2) Depth and succession of soil horizons down to parent material.
- (3) Colour of various horizons.
- (4) Texture of the horizons.
- (5) Structure of the horizons.
- (6) Chemical composition of the horizons.
- (7) Soil water conditions.
- (8) Parent material.
- (9) Nature of cropping or vegetation.

(1) **Surface Features and Altitude.** Most of this information is already on the Ordnance Survey maps, but it is convenient to record such categories as flat, rolling, steep, and broken.

(2) **Depth and Succession of Soil Horizons.** The unit of soil study is the complete succession of horizons down to the parent material from which they have been differentiated. The soil survey should, therefore, include descriptions of all types of soil profile likely to be encountered. The data are conveniently recorded in notebooks with corresponding references to the field map.

(3) **Colour.** Colour is perhaps the most difficult of all soil characteristics. The most important distinctions to be noted in soil surveying are between grey colours, on the one hand, and red and brown colours, on the other. Grey colours are found in arid soils, in the bleached layers of podsol soils, and in soils with impeded drainage. Brown and red colours are found in tropical soils and also in soils of temperate climates formed with complete leaching in the absence of acid humus. Red colours may be conferred by the parent rock as in the soils of the Trias and Old Red Sandstone in England. The presence of rusty-brown, orange, or yellow streaks or mottlings should be particularly noticed, since they are valuable evidence for the occurrence of waterlogging or drainage impedance.

(4) **Texture.** For some purposes, distinctions in texture are of great importance. For ordinary soil surveys, however, it is not practicable to have more textural grades than can be distinguished in the field by personal judgment. In Great Britain the following texture grades are recognized :—

Light Sand . . . . .	Sa
Heavier Sand (or Loamy Sand) . . . . .	Sb
Light Loam . . . . .	La
Medium Loam . . . . .	Lm
Heavy Loam . . . . .	Lb

Clay . . . . .	C
Coarse Silt . . . . .	Za
Fine Silt . . . . .	Zb

Intermediate grades may also be distinguished, such as sandy clay (Cs) and clayey sand (Sc).

In the United States a much larger number of textural grades is recognized. The judgment as to texture obtained in the field is checked from time to time by actual mechanical analyses in the laboratory.

(5) **Structure.** This soil character has been given particular attention by Russian and American soil workers. In Britain, it has probably not been given sufficient importance. This may be due to the fact that British soils are generally moist, in which state structural characters are not so readily observed. In addition to the macro-structure implied by the terms, granular, nut, platy, etc., it is desirable to consider also the micro-structure, noting the character of the small crumbs or fragments and such appearances as the presence of pores.

(6) **Chemical Composition of the Horizons.** We are only concerned with certain chemical tests in so far as they contribute to the general characterization of the profile and may serve as a basis for further exhaustive chemical researches. The following are some of the tests usually made :

(a) The detection of the vertical distribution of calcium carbonate by dropping dilute hydrochloric acid on the whole profile.

(b) The testing of soil reaction in the different horizons.

(c) A thorough investigation of any concretions found in the profile, and their composition ( $\text{CaCO}_3$ , gypsum, ferric oxides, etc.).

(d) The testing of the solubility of the humus in water, dilute ammonia or other solvent. The mobility of humus substances is characteristic alike of forest and of alkali soils. The saturated humus of steppe soils and rendzinas is insoluble unless previously liberated by some acid.

(e) The detection of the presence of ferrous iron, which shows where reduction processes predominate.

(f) The examination (in alkali soils) of the kind, quantity and vertical distribution of water soluble salts.

(7) **Soil Water Conditions.** Both from the standpoint of soil classification and of practical utility, distinctions under this heading are of the greatest importance. It is convenient in the first place to

distinguish soils of free drainage from soils with impeded drainage. The former may be sub-divided into soils which are satisfactory and soils liable to drought. Soils with impeded drainage may be divided into soils with positional water-tables as in the valley bottoms or coastal regions, and soils of elevated regions having impervious strata. Varying degrees of wetness may be distinguished and, in addition, it should be noted whether wetness is continuous or intermittent.

It sometimes happens that excessive wetness may alternate with excessive dryness in the same soil. Changes in level of the water-table in a coarse sand may lead to such alterations. Further, in heavy clay soils, winter wetness may have the effect of restricting root development to the surface horizon. When drought occurs, the moisture within root range is quickly exhausted and capillary rise is too slow to repair the losses by evaporation and transpiration. These circumstances are generally reflected in the character of the natural vegetation, or in cultivated lands, the grass herbage. Indeed, natural vegetation or grass herbage are often the surest clues to the nature of the soil.

The distinctions under this heading are of great importance and can only be discovered by actual examination of soil profiles. Categories such as excessive drainage (dryness), satisfactory drainage, seasonal wetness, and permanent wetness, are recognized.

(8) **Parent Material.** Under this heading the mode of origin, e.g., weathered material in situ, boulder clay, hillwash, etc., must be recognized, as well as its actual lithological character, e.g. basic igneous rock, non-calcareous hard shale or hard grey limestone.

In immature soils, the soil profile may consist entirely of slightly modified parent material without true soil horizons. This is the case in recent alluvial soils such as those of recent reclamations in Holland. There are also other instances in which the actual cultivated soil would appear to be almost unmodified parent material. These may be encountered in regions with rolling topography where erosion has removed the original soil horizons from unconsolidated parent materials. The agricultural soils in such cases are, pedologically speaking, C. horizon material.

(9) **Natural Vegetation and Cropping.** In waste lands, this means a general description of the vegetation. In agricultural lands, notes on the herbage (if grass) or the crop are made.

The above characteristics of the various profile horizons are

examined in pits dug at representative places. A profile pit is opened, generally to a depth of about three feet, or until the parent geological material is reached. The vertical face is then examined and the different horizons are distinguished. Samples are then taken from the different horizons and these are examined analytically in the laboratory. The data serve to give precision to the observational data recorded in the field and also to define the different characteristics in quantitative terms. The identity of difference of profiles recognized in the field often depend on the interpretation of laboratory data. Uniformity of profile over an area is checked by means of auger borings, which also serve to indicate a change of profile as they are extended across the face of the country surveyed.

Soils must, however, be examined in detail in their natural environment, otherwise there is every likelihood of drawing false conclusions. It often happens that a soil in its original state differs entirely in colour from the same soil when it reaches the laboratory. It is easy to understand, for instance, why a soil containing iron in the form of ferrous salts should change its colour by contact with the air. The change ensuing under such circumstances may be so complete as to prevent our detecting the original colour. Another peculiarly local characteristic is the natural structure of a soil, which cannot be ascertained except by examination in situ ; for the moment we lift the soil out of its original position, the structure becomes more or less disturbed, often beyond recognition.

**Soil Maps and Manurial Status.** You must not expect a soil map to give you the manurial status of every field so that you can tell at once what manures and fertilizers it needs. This is impossible, for two reasons : firstly, because time would not suffice for the collection and analysis of soil samples from every field ; and secondly, because such data would only have a temporary value and would change with variations in cultivation, cropping and manuring.

What we aim at showing on a soil map is the occurrence and distribution of the different kinds of soils, having regard to their permanent characters and not to those characters that can soon be changed by manuring or management. Thus, a soil might be changed by good management and liberal manuring from a low into a high condition of fertility. Similarly, continued neglect and exhaustive cropping without adequate manuring might so deplete the plant-food status of a fertile soil that crop returns would not repay the labour of cultivation and seeding. Such changes are temporary and

do not affect the permanent character of the soil. There are, nevertheless, cases where long-continued treatment may alter essential soil characters. For example, when land has been for generations under grass it will acquire characters that will distinguish it from the same soil under continuous arable cultivation. Light sandy soils long under market garden culture, with heavy dressing of organic manures, will also change from their original character. The same may be said of changes consequent on artificial drainage. Thus, whilst short-term changes mainly affecting manurial status are disregarded for survey purposes, more profound changes consequent on long-continued treatment are recognized as being sufficiently important to form the basis of soil differentiation.

#### THE MAKING OF A SOIL MAP

The preliminary work consists in the determination of the character of the soil types and the other soil units that occur in the country or area to be mapped. Detailed knowledge of the internal and external soil features of the area is necessary and can be acquired only through the complete and careful observation of the different types of soil profiles as developed under the various conditions of relief, drainage, vegetation, and parent material. The significance of each soil condition to the agriculture and land utilization of the area must also be studied. All of this work leads up to the determination of what soil types, phases, complexes, or miscellaneous land types are mappable and can be shown without exaggeration on the scale of map that is planned for the area. Following the determination of the soil units, written descriptions of each are prepared and incorporated with general instructions on mapping into what is known as the descriptive legend.

Lacking an accurate base map, the soil surveyor prepares one by measuring distances on the ground and plotting them to scale on the field sheet. The usual scale is 2 inches to 1 mile. Aerial photography is now rapidly doing away with the necessity for making base maps by the older methods of the surveyor.

After the completion of the base map, actual soil mapping, which consists in the placing of soil boundaries, may begin. In this process the mapper does three distinct things. (1) He keeps his location, (2) identifies the soil units of the landscape, and (3) sketches their pattern of distribution to scale on the map. The proper identification of the soil types and other soil units requires constant

observation of the landscape and sufficient examination of soil profiles to enable the mapper always to know the character of the soil before him. In observing the association of soil characteristics with landscape features, the mapper learns to visualize the extent of each soil unit and the pattern of its distribution. External features of the landscape, such as relief and native vegetation, come to be recognized as indicators of the local soil types. Experience and judgment are needed to interpret the landscape in terms of the proper soil units with their corresponding agricultural significance.

After the visualization of the extent of the soil units by the mapper, he proceeds to sketch their boundaries on the soil map. The classification of a soil unit and its boundaries must coincide with actual conditions without omission of important characteristics or exaggeration of minor details. A finished map is not a crude crowding together of areas but a representation of a natural landscape. Not all boundaries have equal significance. One may represent a sharp and distinct break in soils and topographic features, such as the line between a rocky slope and a non-stony flat. Other boundaries may represent transitional conditions, such as the line separating a loam from a silt loam on a long gentle slope.

Most of the soil maps of the United States Department of Agriculture are published on a scale of 1 inch to the mile. Until a few years ago this was also the scale of mapping in the field. Most of the current field mapping is now on a scale of 2 to 4 inches to the mile. Larger scales are employed in the field for particular areas, such as demonstration farms. In areas where erosion control and land use are of immediate concern, the scale of the field mapping is commonly 4 inches to the mile. By the use of the larger scales the mapper is enabled to include the more transitory data that are the result of economic and social influences, such as the location of crops, the use of the land, and the effects of management practices upon production in addition to the relatively permanent data of the physical landscape. This detailed information may be excluded later from the published map on the 1-inch-to-a-mile scale.

**Utilization of Soil Maps.** The function of a soil survey is to classify, locate on a base map, and describe the nature of soils as they occur in the field. The soils are grouped into series and types on the basis of their profile characteristics. The field man, since his work is localized, concerns himself mostly with series and

type separations, giving the broad regional distinctions but little consideration.

As the series and type identification progresses in the survey of any area, the territorial location of each individual soil is shown on a suitable base map. Such a map is reproduced in colour and accompanies a bulletin containing a discussion of the topography, climate, agriculture, and soils of the area under consideration. Each soil type is minutely described and suggestions as to its practical management are often made.

Broadly speaking, any individual or agency, interested in either the specific character of individual land units or in the broader aspects of regional land use and land planning holds the soil maps to be indispensable. The use of the soil survey map and report in determining the suitability of certain lands for irrigation or drainage projects illustrates the type of work dependent upon the information of the soil map.

With some idea of the relationships among the soil units of the map and their significance for agriculture, the reader can visualise much more effectively the landscape pictured by the map. Without the report the map is limited in its usefulness for agriculture. The reader who is interested in any particular area, therefore, is forced to turn to the soil descriptions of the report for a knowledge of soil characteristics, as well as for information concerning the present use of the land.

### PRACTICAL MAPS

Since a practical farmer is unable, however, to make head or tail of a complicated map of the kind postulating expert knowledge, separate *Practical maps* must be prepared from the basal map.

Local authorities, county agents, and others working in a locality can use a soil map to prepare a series of maps bringing out different characteristics of the soils of a county. Thus the soil units could be drawn upon a drainage map and classified as (1) excessively drained (droughty soils); (2) well-drained; (3) imperfectly drained; and (4) poorly drained. Instead of a map, of say, 50 colours, one of 4 would result. Similar differentiations and combinations might be made as to conditions of texture, structure, colour, stoniness, relief, or erosion. A map might show the distribution of soils with different lime requirements. Other maps might show the suitability of soils for corn, lucerne, or tobacco. A

general classification as to suggested land use for short rotations, long rotations, permanent pastures, and forests might be prepared. No two maps would agree in outline of boundaries, although certain characteristics would appear to be associated with each other. The fact that many types of maps may be prepared from a soil map illustrates the complex character of the soil unit.

It must not be thought, however, that the present units of the soil map have little meaning in relation to the chemical constitution of the soil. Fortunately, as a result of investigations in the laboratory and on experimental plots, correlations can be made between the observable features of the soil and its chemical character and productive ability. Again, correlations can be made from the experience of farmers. A part of the work of the future is to investigate more completely the chemical and nutritional properties of the mappable soil types in order to determine which characteristics are merely accidental and which express the inherent character of the soil.

The actual practices of farm management of individual farms, fields, or soil types contribute greatly to what may be called the accidental presence or absence of a particular plant nutrient in the surface soil. This effect is not to be confused with the more stable chemical constitution of the soil as developed from the parent material under the conditions of the natural environment. Present conditions of fertility (referring to the supply of plant nutrients) of any land managed by man depend upon the relative influences of these two factors of inherent fertility and management. It must be added, however, that the complex of all the characteristics of the natural soil enters into the determination of what the results of man's techniques will be.

The soil map, by delineating those soil areas that possess similar levels of inherent fertility and similar physical characteristics which together influence soil productivity, can be used by the farmer to guide him in the use of specific recommended practices—practices developed by the investigation and experience of others on similar soils. For example, it may have been found experimentally or through the experience of farmers that certain soil types can be cropped to corn safely only once in 4 years; that other types may grow corn safely in 3 years out of 4, provided the nitrogen supply is maintained by a green-manure crop; and that other areas cannot be recommended for cultivation under any feasible system of

management. Other soils may be known to be naturally low in potash, or to respond to phosphates, or to be benefited by fallow ploughing. In this way the soil map serves to bring to the farmers the findings of experimental research. With the help of the auxiliary maps farmers are really enabled to obtain all the information they require in matters of interest to them ; and that is what practical soil maps are intended to do.

**Other kinds of Soil Maps.** Another great group of soil maps consists of those special maps which are drafted for a single special purpose. In principle, the only difference between them and the former category is that they deal with only one particular soil type—e.g. alkali soil types. They may be comprehensive or local. Like all such maps, this soil map is entirely one-sided.

In Denmark and Germany—and recently in Hungary too—soil maps have been drafted which show only the pH value of the soils. In districts in which the excessive height of the water level is injurious and it would seem expedient to drain the water, maps have often been drafted showing the height of the water level. Other soil maps ascertaining the minimum air capacity of the soil, its pore volume and absolute water capacity, enable soil scientists to tell where drainage may be expected to produce positive results. Maps showing the mechanical composition of the soils, enable them in addition to calculate the most advantageous distance and depth at which to lay the drainpipe.

#### GEOGRAPHIC ASSOCIATION OF SOIL UNITS

The simple units—series, types, and phases—must be shown upon large scale maps in order that their relationship to one another, to the other local features of the landscape, and to the detailed pattern of human occupancy may be understood. In order that broader relationships may be understood and regional problems attacked, smaller scale maps showing the distribution of soil groups in the higher categories, especially the great soil groups, must be compiled.

It should be stated, however, that, in the present state of our knowledge, it is, perhaps hazardous to attempt to give any general view of the soils of the world, for large areas remain pedologically unexplored. Such information as can be given about the soils of these regions is, to a large extent, conjectural, and based on the collateral evidence of climate, topography, and vegetation. It is

only to be expected that fuller information is available in some countries than in others.

### PRODUCTIVITY RATINGS

A feature, however, that has received considerable attention in America during the last decade is the preparation of soil-productivity ratings. The American Soil Survey Division has adopted the policy that such ratings are to be included in the soil survey reports, and where possible the current reports of counties and areas in various parts of the country carry these ratings. This policy is a recognition of the fact that the scientific classification of soils should lead to an understanding of the practical aspects of soil productivity and land utilization. Morphological distinctions have physical and chemical attributes significant for the growth of crop plants, grasses, and trees.

Factors controlling the inherent productivity of the soil vary from place to place. Over broad areas, differences in climate may be of extreme importance. Locally, however, differences in productivity are associated usually with differences in topography, drainage, or parent-soil material. For example, the degree of stoniness may be the most important factor. Again, the depth of bedrock or the calcium content of the parent material may be the dominant factor influencing local, though marked, differences of productivity. It should be emphasized that soil productivity and soil fertility are not the same. Fertility refers only to the content of plant nutrients. Because of imperfect drainage, for example, a soil of high fertility may be much less productive than one of lower fertility.

The productivity-rating tables, bring out both the local and the broader regional differences among the soils by establishing standard yields as points of reference. The standard yield (100) for each specific crop represents approximately the average yield obtained without such amendments as fertilizers and lime on the best soil of the region in which the crop is principally grown. Thus, the exceptional and not extensive soil types that are especially well adapted to a particular crop receive indexes above 100. If the index were not on this basis, it would be necessary to establish a standard so high that large areas known for their production of a crop might receive relatively low ratings. The standards refer to the inherent ability of the soil to produce the particular crop under

the common practices of tillage without the use of amendments.

This productivity rating represents an attempt to give a quantitative expression to the productive capacity of a soil. It is the crystallized expression of the experience of the people who have used or are using the land. In the soil-survey reports tables are given of productivity ratings or indices in relation to all the main crops of the district. (See Table 30).

TABLE 50

	Maize		Wheat		Rye		Lucerne		Sugar Beet		Productivity Grade	
	A	B	A	B	A	B	A	B	A	B	A	B
Miami Loam	70	90	70	100	80	100	70	90	60	70	3	1

The two sets of columns A and B refer respectively to the percentage of the standard yield of the crop obtainable with (A) common practices of managements (average farming) in the area, and (B) the best current practices. The standard yields have been selected to represent the approximate average yield obtained for that crop on the more extensive and widely developed soils of the regions in the United States in which the crop is a principal product. The standards refer to average yields obtained without the use of amendments, although it has been arbitrarily agreed that nitrogen fixed by legumes and manure produced from feeding stuffs grown on the land are not to be considered as amendments, e.g., the standard for maize is 50, and for wheat 25, bushels per acre; for clover and timothy it is 2, and for lucerne 4, tons. Under average management for the county in question the Miami loam will yield 35 bushels of maize and 17.5 bushels of wheat and under first-class management 45 bushels of maize and 25 bushels of wheat. The same soil might be differently rated in another county.

From the example given above it would appear that the Miami loam is used predominantly for cereal growing since its productivity grade corresponds to its productivity ratings with respect to cereals. The difference between the (A) and (B) ratings is a measure of the soil response to good management.

The yield figures from which the ratings are determined are estimated from data obtained by the soil surveyor from interviews with farmers and county officials, elevator records, personal observations, etc. The chief difficulty in determining ratings from

yield data is to establish a standard of management and to estimate the degree of divergence from the standard on each farm. The usual standard of management is defined as that which will maintain soil productivity of or near the level of the "nearly virgin" soil.

An inductive method of rating the agricultural value of soil has been suggested by R. E. Storie. Regardless of actual cropping experience with the soils, Storie compiles the ratings from percentage values accorded to certain characteristics of the soil profile. Three "factors" are used, one referring to the general character (excluding texture) of the profile and particularly to the stratification and degree of weathering, one referring to the surface texture, and a third to "soil-modifying conditions," such as drainage conditions, acidity and alkalinity, erosion, etc. The values of these three factors, expressed as percentages of the optional conditions for plant growth are multiplied together to obtain the rating, and the product is expressed as a percentage of the maximum. The advantage of multiplying instead of, as is more usual, adding the points credited to each soil characteristic is that thereby any one abnormal factor can dominate the final rating. Thus a soil may have excellent profile conditions rated at 100 for the first factor, excellent texture rated at 100, for the second factor, but bad alkali accumulation rated at 10 for the third factor. The product of the three gives a percentage rating for the soil of 10, according with the fact that despite other favourable conditions the alkali renders the soil practically unproductive. On an addition basis the rating would have worked out at 70 per cent.

In Germany, a somewhat similar inductive method, devised to be comprehensible to the unschooled farmer, has been employed. Two factors are multiplied together to get the productivity rating or "Bonitierung." One relates to the genetic soil type to which values are given ranging from 10 for chernozems to 4 for podzols with hardpan, the other relates to the textural variety to which values are given ranging from 10.0-8.8 for loams, 8.8-6.5 for sandy loams, 8.4-6.0 for clays, 4.1-2.0 for sands. Thus a loamy chernozem developed on loess would get the highest possible rating of  $10 \times 10 = 100$ , and a sandy podzol would get the lowest rating of  $4 \times 2 = 8$  given to agricultural soils. The values allotted to the different soil types and varieties are determined from yield data obtained from numerous sample soils. It is not clear to what extent differences in management are taken into account.

*The Chemical Aspects of Soil Fertility*

SOIL fertility is the ability of the soil to give a generous return for expenditure in labour, in seed, and in manure.

The history of agriculture affords many instances of the way in which the yield is pushed up by steadily removing the limiting factors that had been keeping it down. From the medieval writers we may infer that 10 bushels was a common crop of wheat in their day. This was obtained on unenclosed land by the use of such stable manure as was available. Later on, when the land was enclosed, it could be kept cleaner and competition of weeds was therefore reduced : still later, rotations were gradually introduced ; liming and chalking were more carefully done ; drainage was attended to. In the middle of the nineteenth century artificial manures were introduced and tillages were improved ; still more recently improved varieties and better seed have been available so that now 40 bushels are readily obtained by good farmers. Each improvement has consisted in removing some factor that was keeping down the yield to a certain level.

The fertility of the soil is not a wasting asset like the reserves of a coal- or oil-field, and few systems of farming are bad enough to be described as " mining the soil." The essential properties of the soil depend on the way in which the parent rock material has been modified by the combined action of weather, micro-organisms, plants, animals and man. The top few inches of soil are the most important. They may have taken thousands of years to form, but they may be lost or seriously damaged in a few years. The sub-soil is normally much less fertile, and it may be so raw that only small quantities can safely be brought to the surface at a time. Under favourable conditions it acts as a useful reservoir for water, and its supply of available nutrients, though small, may be tapped and restored to the surface by deeply rooting plants.

It is to the primeval lithosphere, or rocky surface of the globe, that plants, animals, and man owe the ultimate origin of the dozen or more mineral elements that are necessary for their existence.

The plant is the great intermediary by which certain elements of the rocks, after their conversion into soil, are assimilated and made available for the vital processes of animals and man. The simple inorganic constituents of the atmosphere and soil are selected and built up by the plant into protein, sugar, starch, fat, organic salts, and other substances of marvellous complexity. The substances thus synthesized by the plant are subsequently elaborated, with additional selections and removals of elementary components, by the vital processes of the animal body into flesh, blood, bones, and other structural materials. To investigate the progressive steps of these transformations of matter by plant and animal life and to make them conform so far as possible to man's special requirements are the chief aims of agricultural science. Now we are concerned with one aspect alone, namely, the soil conditions favourable for plant growth.

Chemists, physicists, geologists, bacteriologists and others have all studied the soil, but those who have done most would be the first to admit that we really know very little about it, and much still remains to be discovered.

The farmer is chiefly interested in soil as the place where his plants grow, and this aspect of the soil, its relation to plant growth, is particularly investigated in laboratories. Before it can seriously be studied we must first know what the plant requires from the soil: we can then proceed to see how and in what way the soil fulfils these requirements.

When we study the growth of plants we find that quite a number of factors are involved, and it will be convenient if we set these out at length. For the growth of plants, we must have:—

(1) Light; (2) Temperature; (3) Carbon dioxide; (4) Moisture; (5) Oxygen; (6) Root hold; (7) Plant nutrients; (8) Absence of Injurious Substances; (9) Absence of excessive competition; (10) Unknown factors.

(1) **Light.** The building up of plant material is a process requiring an external source of energy, and this is obtained from sunlight. The assimilation of carbon dioxide by the leaves of green plants ceases as soon as light is cut off.

(2) **Temperature.** Plant growth is strongly affected by

temperature. Most of agricultural crops, including grass, make very little growth below about 42 °F. The rate of growth increases as temperature rises, and reaches a maximum at a temperature, called the optimum temperature, that varies with the crop. Thus, whilst crops such as barley and oats may have 60 to 65 °F. as optimum temperatures, tropical crops such as sugar cane and pineapple may make their best growth at 75 to 80 °F.

Temperature is largely a question of water supply, since a given amount of sunshine will raise a dry soil to a higher temperature than a wet one. But it depends also on the slope of the land, a south slope being warmer than a north slope ; also on whether the soil is bare or shielded from the sun by a cover of vegetation.

(3) **Carbon dioxide.** The compounds of which plants are composed, starches, sugars, fibres, fats and proteins, are all compounds of carbon, and this carbon is obtained from the carbon dioxide present in the atmosphere. Under the influence of sunlight, the green colouring matter of plants is able to effect the remarkable synthesis whereby carbon dioxide and water yield starch and oxygen.

For most practical purposes the limiting factors which determine a state of infertility are to be found in the soil conditions, but when soil conditions are at their best the carbon dioxide supply in the air remains a limiting factor. Investigations in Germany and elsewhere have shown that increasing the carbon dioxide content of the air up to a certain point results in enhanced growth. This consideration may have an important effect upon glasshouse work. There is also some evidence to indicate that under field conditions the carbon dioxide formed during the decomposition of organic matter has a considerable effect upon the crop and that it is one of the beneficial consequences of using farmyard manure.

(4) **Moisture.** Not only does plant material contain considerable proportions of water, but water is absorbed in large amounts by the roots and transpired by the leaves.

The water supply comes from the rain, but if the soil lies on the lower part of a slope it may derive further quantities from the land higher up. Crops vary greatly in their need for water, according to the conditions. In hot dry climates from about 300 to about 900 lb. of water may be transpired by the plant for each lb. of dry matter made. The water requirements per lb. of dry matter of the common crops in these circumstances are as follows :

- Most economical : (300 lb.) . . Millet, Maize.  
Less economical : (400-600 lb.) . . Sugar, beet, barley, oats,  
potatoes, cow-peas.  
Least economical : (800-900 lb.) . . Lucerne, clover, grass, flax.

In humid countries it is not usually practicable to add water except in market gardens where spray irrigation is used, and in some meadows where flooding is possible. In dry countries irrigation is usual, but it needs to be done with great care or much harm results. Control of the water supply is effected in farm practice by adding farmyard manure, thereby increasing the power of the soil to hold moisture, and by bringing the soil into a good tilth.

Controlling the watering of the soil has a considerable effect on the yield of crops. Von Seelhorst showed that barley growing in a soil watered only to half its full water-holding capacity produced twice as much root as when the water was maintained at three-quarters the full capacity.

(5) **Oxygen.** Plant roots require oxygen for their respiration. If air is excluded from the soil by waterlogging, plant roots cannot live. The development of roots in a soil is confined to those layers that are aerated.

Air supply is closely bound up with the water supply because the only space available for air is that part of the pore space that is not filled with water. The supply is thus determined by tilth and drainage.

Some plants need more air than others for their roots : maize and peas can hardly get enough, while rice and some of the *Salix* family can do with very little. Good aeration favours the development of a large fibrous root system, vigorous growth of large green leaves, and good setting and developing of fruit. Root respiration is closely connected with the uptake of plant nutrients.

Air and water, however, are usually supplied rather easily because of the open condition of the soil. Oxygen functions as a chemical and biochemical agent while water acts as a nutrient as well as a solvent. By its circulation it not only promotes an interchange and interaction of constituents but it continually brings nutrients into contact with the absorbing surfaces of the roots.

The more the water supply is increased the less are the facilities for aeration, and the lower is the temperature of the soil. These three factors are all interdependent, and the improvement of any one of them involves the suppression of one of the others.

(6) **Root Hold.** The soil must have sufficient stability for plants to root in it. The comparatively loose and friable condition of most soils presents ample foothold to the ramifying roots. In some cases, however, the presence of a compact layer or a lack of adequate drainage may interfere with the root spread.

The layer of soil in which plant roots can develop freely is deepened by the following methods :—

(1) Drainage, where a water-table limits root development.

(2) Deep ploughing or cultivating to break up a compact layer. This, however, appears to be effective only where organic matter is added to the newly broken lower depth.

(3) The growth of deep rooting crops such as lucerne, the roots of which can penetrate the subsoil, and, on dying, enrich it in organic matter.

(4) Soil can also be deepened by shattering the underlying rock or hard layers with explosives. This method is not in general use, though demonstrations of its value have from time to time been given in the United States by the du Pont organisation and others, in South Africa and elsewhere. A notable example is the pulverising of the soft rock in Algeria by nitro-explosives. Holes are bored about 3 feet into the rocky surface ; charges are inserted and fired. The rock is broken, and much is pulverised. Large stones can be taken out for building and other purposes. The pulverised material is levelled, and manured with sheep-dung and a complete mixture of special fertilizers. The rain, when it comes, is torrential, but instead of running off as usual and washing away the soil it soaks in and remains stored up for the plants. Potatoes, vines, and fruit trees are grown with great success. Piedallu states that many thousands of trees have been planted and are growing rapidly, and that parks, gardens, and vineyards are thriving, where, but a little while ago, there was nothing but a hot and stony waste.

(7) **Plant Nutrients.** By this we mean the elements absorbed by the roots of plants. It was formerly thought that the essential plant nutrient elements were nitrogen, phosphorus, calcium, magnesium, and iron. Recent work has extended this list, and we may now add boron, manganese, copper, iodine, zinc, and cobalt. Other elements will doubtless be found to be essential. Table 51 shows the essential nutrient elements and their sources.

**Amounts of the Primary Nutrient Elements Present in Mineral Soils.** Although soils vary greatly in chemical composi-

TABLE 51  
*Essential Nutrient Elements and their Sources*

Essential Elements Used in Relatively Large Amounts			Essential Elements Used in Relatively Small Amounts	
Mostly from air and water	From Soil Solids		From Soil Solids	
Carbon ...	Nitrogen ...	Calcium	Iron ...	Copper
Hydrogen ...	Phosphorus...	Magnesium	Manganese ...	Zinc
Oxygen ...	Potassium ...	Sulphur	Boron ...	

tion, it is possible to indicate the percentage range within which the primary nutrients are ordinarily found when a number of surface soils is considered. Also for the sake of brevity an average representative analysis may even be ventured. (Table 52).

TABLE 52  
*Amounts of the Important Constituents of Mineral Soils*

Constituents	Ordinary Ranges in Percentages that may be expected	Representative Analysis	
		Percentage	Lbs. to Acre-Furrow slice
Organic Matter ... ..	0.50-10.00	4.00	80,000
Nitrogen (N <sub>2</sub> ) ... ..	0.03- 0.50	0.20	4,000
Phosphoric acid (P <sub>2</sub> O <sub>5</sub> ) ... ..	0.03- 0.40	0.15	3,000
Potash (K <sub>2</sub> O) ... ..	0.20- 4.00	2.00	40,000
Lime (CaO) ... ..	0.10- 5.00	0.60	12,000
Magnesia (MgO) ... ..	0.20- 2.50	0.60	12,000
Sulphur trioxide (SO <sub>3</sub> ) ... ..	0.03- 0.40	0.15	3,000

It is evident that most surface soils contain a considerable amount of organic matter. Yet this constituent is usually a critical factor due to its rapid oxidation and ready disappearance. Its inactivity is seldom serious except in very acid or very dry soils. Nitrogen and especially phosphoric acid are always present in comparatively small amounts. While the nitrogen is generally rather readily available since it is carried by the organic matter, the phosphoric acid is more or less insoluble and as a result critical as a nutrient element. In fact, when commercial fertilizers become necessary, phosphorus is generally the first element to be added.

Potash, in marked contrast to the phosphoric acid, is usually

plentiful except in sandy soils. The main problem is one of availability. Lime shows great variations but it is generally present in lesser amounts than is potash. When it is lacking the soil becomes acid, it is therefore, generally added to correct this condition although the direct nutrient influence of calcium cannot be disregarded. Magnesium, besides its importance as a nutrient, functions in the soil much as does calcium. Although it is deficient in some soils, it is not generally a limiting factor. Most agricultural limes contain some magnesium.

Sulphur, while usually no more plentiful than phosphoric acid, is more readily available since it is carried in great proportion by the organic matter. It becomes critical only under certain conditions. The addition of sulphur in farm-manure and rainwater, and in such fertilizers as superphosphate, ammonium sulphate, and potassium sulphate tends in an automatic way to prevent a possible deficiency.

**Forms in which the Primary Nutrient Elements occur in Soils.** An examination of a representative soil will soon reveal that in a general way the nutrient elements exist in two conditions :

- (1) Complex and rather insoluble forms.
- (2) simple compounds usually soluble in the soil-water and rather readily available to higher plants.

Due to the chemical and biochemical processes at work in the soil the general trend and the final disposition of the elements is from the complex to the simpler forms. Thus the nutritional needs of higher plants are served as soil evolution progresses.

This does not mean that the reverse process, that of synthesis and increased complexity, does not normally occur in soils. In fact, such reactions are continually taking place and in many cases are of tremendous practical importance. The building of elemental nitrogen, nitrates and ammonium compounds into proteins by micro-organisms, the reversion of soluble phosphates to complex and insoluble forms, and the tying-up of iron, manganese, and aluminium by a change in pH are ample illustrations of such reversible reactions.

Since the simpler and more soluble constituents of soils, especially those of a humid region, readily disappear in drainage or are synthesized by micro organisms and higher plants, the greater proportion of each nutrient is left existing in the soil in a complex condition. From thence they gradually disappear and become available through various processes of simplification. The complex group

is thus a repository, the fertility of the soil depending not only on the total amounts of the various nutrients present but also on the ease with which transfer is made to simple and available forms.

Our knowledge of animal and human nutrition, made slow progress until foods could be analysed into nutrients ; first, into carbohydrates, fats and proteins, and, later, into individual amino-acids, carotene and the rest of the vitamins, calcium and other mineral elements. Similarly in crop nutrition, the recognition of the effects of simple nitrogen compounds and ash constituents provided a scientific basis for manuring and for maintaining soil fertility.

(8) **Absence of Injurious Substances.** This is a kind of negative factor, but there are many instances of plant growth being depressed by harmful constituents in the soil. Among such harmful constituents we may mention acids, sodium salts and compounds of metals, such as lead, zinc, copper or nickel, if present in sufficient amount.

The reaction (acidity or alkalinity) of the soils is an important factor influencing plant growth directly or indirectly. Under strongly alkaline conditions, harmful effects accompany the development of excessive amounts of alkali carbonates. In very acid soils there may be injurious concentrations of certain constituents, such as aluminium and manganese, that are only slightly soluble at a moderate degree of acidity. The microbial activities of the soil are greatly influenced by the soil reaction. Availability of phosphorus is affected by factors related to the soil reaction. The degree to which nitrate and ammonium nitrogen may be assimilated by the plant is also a function of the acidity or basicity of the soil solution.

Occasionally soils are infertile through an excess of some toxic elements, such as zinc. (*See* chapter 9). Animals may be more sensitive than crops. Thus excess molybdenum is responsible for the troublesome "teart" pastures of Somerset, and excess selenium gives poisonous herbage in parts of South Dakota in America.

Soils may be infertile, at least for certain crops, through deficiencies of a number of other elements. Thus, on some heath and light fens reclaimed by liming, sugar beet, oats and potatoes may suffer from shortage of manganese. Other soils lack boron. Sometimes grass has insufficient cobalt to support healthy animals (*See* Chapter 9).

Freedom from these adverse chemical conditions is largely subject to intelligent control. For example, excess salts may be leached from the soil and harmful alkalinity corrected by the application of gypsum or sulphur, provided plentiful water and adequate drainage can be supplied, as discussed in Chapter 13. Adverse acidity may be overcome by liming. (*See* Chapter 12).

(9) **Absence of Excessive Competition.** The agricultural crop may be depressed by excessive competition by weeds.

(10) **Unknown Factors.** Finally, there are the unknown or little understood factors in plant growth. It seems likely that there may be certain substances that have a specific effect in promoting plant growth. Indeed, recent work has shown that certain compounds present in the urine of animals stimulate germination and root development. This will be discussed at a later point.

We can see now how complicated is the problem of soil fertility. We have ten factors or groups of factors, all of which must operate satisfactorily in order to obtain satisfactory plant growth. If nine of the ten factors are satisfactory, whilst the tenth is unsatisfactory, then this tenth factor becomes the limiting factor. If any factor for example, water supply, is the limiting factor, that factor must be adjusted in order that production may be increased.

We have spoken of ten factors governing plant growth. Actually it is not even as simple as that, for many of these factors might be better described as groups of factors or composite factors. Under plant food we understand the supply of a dozen or more elements. Not only may the supply of any one of these elements be a limiting factor but there are all kinds of complex inter-relationships, whereby excessive supply of one element may affect the absorption of another element. Further, we have to consider that an element, such as copper, that is necessary in traces for plant growth, may become an injurious factor if supplied in too great quantity.

Whilst the cultivator can modify certain factors in a direction favourable to plant growth, other factors are outside his control, or can only be controlled to a limited extent. Thus light and carbon dioxide are, practically speaking, uncontrollable. Water supply is governed mainly by rainfall, or artificial irrigation.

It is in the plant nutrient group of factors that the farmer can most successfully intervene, for he can readily supplement deficiencies in the soil by the use of manures and fertilizers.

Fertility must always be considered in relation to the crops

grown. The adaptation of certain crops to certain soils has long been known.

We have presented soil fertility as a complicated and multi-dimensional problem, for such it is, even if we take account only of the known factors in plant growth. Soil fertility is not a matter simply of abundant supplies of nitrogen, phosphorus, and potassium. Neither can infertility be cured simply by loading farmyard manure and artificial fertilizers into the soil. Soil fertility consists rather in the favourable operation of a number of factors, some of which are known and understood, whilst others are little understood, and yet others unknown. The great achievements of the past century have greatly increased the power of Man over Nature. Can we look forward to such a mastery of the problems of the soil and the growth of plants that future crop yields will make our present yields appear as insignificant as those of memorial times appear to us? A close study of all the factors affecting crop growth, and in particular the water conditions in soils, would make possible very considerable increases in crop yields.

### ✓ PHOSPHATE FIXATION IN SOILS AND ITS EFFECTS ON SOIL FERTILITY

It has long been known that, while considerable amounts of nitrogen and lime together with small amounts of potash are washed out of soils in the drainage waters, the loss of phosphate is always extremely small. This is so even where heavy dressings of water-soluble phosphate such as superphosphate have been added. In fact the phosphate added to most soils moves downwards very slowly indeed. In cultivated soils there is generally very little penetration beyond the cultivated layer. whilst in grassland the phosphate often fails to penetrate more than about two inches. The reason for this is that easily dissolved forms of phosphate when added to soils are changed into forms which are more difficult to dissolve. This change is known as "phosphate fixation." Thus, phosphate fixation in soils means the conversion of soluble forms of phosphate into less soluble forms, and from the practical point of view it has very important consequences.

**Practical Importance.** This lies in the fact that fixation prevents full use being made of phosphate fertilizers. This happens in two ways :—

1. *Decrease in availability.* Plants obtain most of their phosphate from the more soluble forms present in soils. These constitute most of what is called the "available" phosphate, which is always only a small fraction of the total amount present. Some of the forms in which phosphate is fixed are so difficultly soluble that they are for practical purposes unavailable, i.e. of very little use to plants. In ordinary soils it is generally the case that only about 20 per cent. of the phosphate added is recovered in the crops before it becomes necessary to add more in order to keep up the yields. If no more were added, some of the remainder would be slowly recovered, but at the price of much lower yields. From the farmer's point of view a great deal of the phosphate added is just locked up in the soil.

2. *Decrease in penetration.* If the phosphate does not penetrate to where the roots are most active plants cannot make full use of it. In this way, fixation often reduces greatly the efficiency of phosphate fertilizers, especially where, as on grassland, they are broadcast on the surface and not cultivated in.

In view of the great practical importance of fixation it is very desirable to know something about the ways in which it takes place in different soils and under different conditions. In fact, this is necessary before steps can be taken to reduce its undesirable effects and improve the efficiency of phosphate fertilizers.

**Types of Fixations.** There are two main types, viz. : Biological Fixation and Chemical Fixation, which take place as follows :—

(1) **Biological Fixation.** This is brought about by certain soil organisms which build phosphorus into their bodies. In this way, inorganic forms of phosphate, such as superphosphate, are converted into organic forms which may be regarded as belonging to the organic matter of the soil. These organic forms of phosphate are of no direct value to plants. Some of them, however, are slowly converted back into inorganic form by other bacteria and in other ways, and may thus become available again to some extent.

(2) **Chemical Fixation.** This is the more important type and is largely brought about by the mineral portion of the soil. It takes place in two main ways.

(a) *By absorption.* Certain insoluble forms of iron and aluminium together with certain silicate minerals present in the clay portions of soils, absorb dissolved phosphate from the soil water. This type of fixation is very widespread, especially in heavy soils, and is greatest under acid conditions. Heavy, acid soils can fix

very large amounts of phosphate in a very unavailable state. The absorbed phosphate slowly undergoes further changes giving rise to even more insoluble mineral phosphates of iron and aluminium which are about the most unavailable forms of phosphate found in soils. This type of fixation is somewhat analogous to the taking up of water by a sponge. When only a small amount of water is added to a dry sponge it is held very tightly, but as more water is added it becomes less tightly held and more easily squeezed out. In a like manner, the reserve of phosphate in the soil must be built up to a certain extent before the phosphate becomes available, and until this has been done very little benefit will be obtained from any soluble phosphate added. This point is of the utmost practical importance.

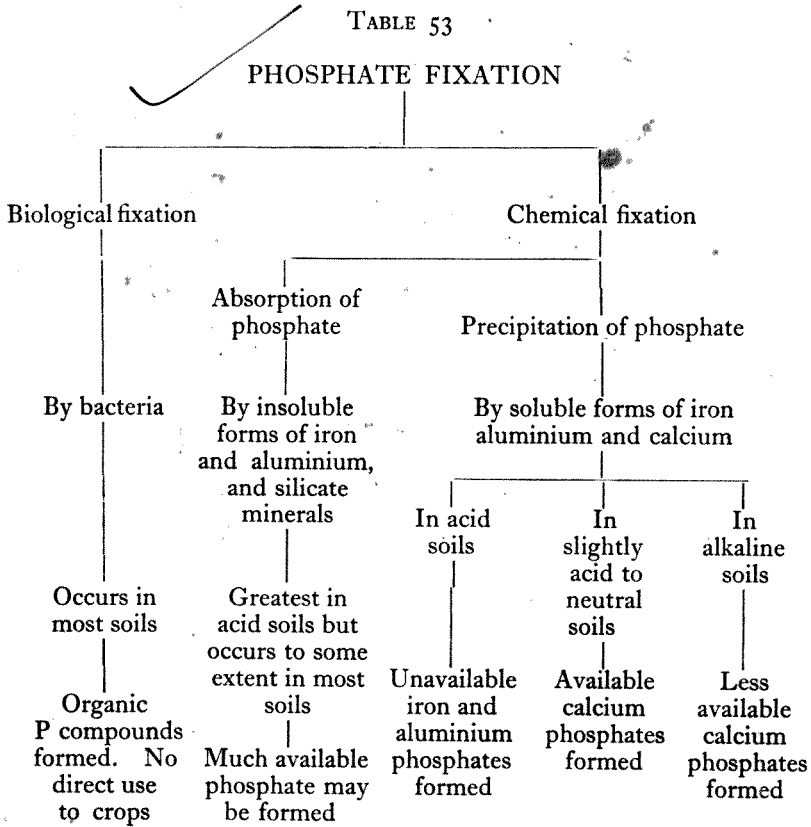
(b) *By precipitation.* This type of chemical fixation differs from the one just described in that the substances which cause it are themselves soluble. It is chiefly brought about by soluble forms of iron, aluminium, and calcium. When these are present in solution in the soil water and a soluble phosphate such as superphosphate is added, they unite chemically with it to form relatively insoluble phosphate compounds. These are deposited in solid form in the soil. This type of fixation thus consists of the precipitation of relatively insoluble phosphates of iron, aluminium and calcium, which are of varying value to plants. The extent to which these different phosphates are precipitated depends very much on whether the soil is acid or not. The main tendencies are as follows :—

(i). *In acid soils.* Fixation is mainly in the form of iron and aluminium phosphates which are least soluble and most readily formed under acid conditions. In the newly precipitated state they are of some use to plants, especially if the soil is not very acid. With time, however, they undergo further changes, to give extremely unavailable mineral phosphates, and, generally speaking the iron and aluminium phosphates of soils are of little use to plants.

(ii). *In slightly acid to neutral soils.* Fixation is mainly in the form of calcium phosphates. Iron and aluminium phosphates are also formed to some extent and if there are soluble forms of manganese present some manganese phosphate may be precipitated as well. The calcium phosphates formed under these conditions are about the most available forms of fixed phosphate that exist in soils. In time, however, they, too are liable to become converted into a very unavailable form, namely, a mineral phosphate called apatite.

(iii). *In alkaline soils.* Fixation is again mainly in the form of calcium phosphates, but of a more insoluble and less available type. The unavailable mineral phosphate, apatite is quite common in alkaline soils. There is no precipitation of iron and aluminium phosphates as such, because they are soluble under alkaline conditions. Magnesium phosphates, however, are rather insoluble in alkaline soils and are precipitated to varying extents, but these are usually quite available forms.

The whole process of phosphate fixation is illustrated diagrammatically in Table 53.



**Ways of Combating Fixation and Increasing the Efficiency of Phosphate Fertilizers.** There are several measures

which can be adopted in practice. These can be summarized under the following heads :

- (1) Maintaining favourable soil conditions :
- (2) Using suitable forms of phosphate :
- (3) Using efficient methods of applying phosphate.

(1) **Maintaining Favourable Soil Conditions.** In practice this amounts to :—

- (a) Liming acid soils.
- (b) Maintaining general fertility.

(a) *Liming acid soils.* Adequate liming of acid soils is of paramount importance. It has several very desirable effects.

(i). It reduces the amount of phosphate fixed in unavailable forms by decreasing the acidity and causing precipitation of available calcium phosphates. As already emphasized, fixation in unavailable forms is least under slightly acid to neutral conditions. Liming also helps to keep the very minute particles of clay bound together in granular form, making it still more difficult for them to fix phosphate. This is particularly important in heavy soils. There is plenty of evidence from field experiments to show that water-soluble phosphate fertilizers such as superphosphate are not only much more effective but remain so for a longer time when the soil has been properly limed. The lime is most effective when allowed to become thoroughly incorporated in the soil before phosphate is applied.

(ii). Liming releases some of the unavailable phosphate present in soils, especially if they have been receiving heavy dressings of phosphate in the past. In particular, liming helps to break down the organic forms of phosphate which, as already mentioned, are of no direct value to plants. Infertile acid soils are particularly rich in organic phosphate, which often amounts to half the total phosphate present. In some soils, liming may, for a while do away with the need for phosphate. It should not, however, be regarded as a substitute because continual liming without adding any phosphate soon depletes the reserves of phosphate in the soil.

(iii). Liming acid soils until they are just slightly acid, not only helps to ensure an adequate supply of available phosphate, but also makes it easy for plants to take it up. Some plants cannot take up enough phosphate to meet their needs, even when there is plenty

actually dissolved in the soil water. They take up phosphate best under slightly acid to neutral conditions.

(iv). In well-limed soils, soluble salts such as muriate of potash and sulphate of ammonia tend to increase phosphate availability. In acid soils, on the other hand, they tend to make the iron and aluminium compounds of the soil more active and may cause increased fixation in unavailable form.

Adequate liming has, of course, several other very beneficial general effects on soils, but from the point of view of phosphate availability alone its importance cannot be over-emphasized.

(b) *Maintaining general fertility.* The presence of adequate supplies of phosphate in the soil is a factor of the greatest importance in the development of plant roots, but plants cannot make full use of the phosphate supplied to them unless other soil conditions are also favourable.

### (2) Using Suitable Forms of Phosphate.

*Soluble phosphates.* Water-soluble forms of phosphate such as superphosphate are of the greatest value as fertilizers. Being water-soluble, however, they are not only readily taken up by plants, but are also rapidly fixed. In a way that it may be said that they dissolve more rapidly than plants can take them up, the unused portion being fixed by the soil. For this reason much attention has been paid to the use of the less soluble forms.

*Insoluble phosphates.* Water-insoluble forms of phosphate, such as ground mineral phosphate, bone manures, basic slag and reverted phosphates, are far less rapidly dissolved in the soil and, as a result, are less rapidly fixed. Where fixation in unavailable forms is serious, e.g., in acid soils, some of these materials may be used with advantage. In general, however, superphosphate is not easily surpassed.

(3) **Using Efficient Methods of applying Phosphate.** Fixation occurs most readily when phosphates are broadcast in powdered form and mixed up with the whole mass of cultivated soil. The efficiency of phosphate fertilizers can be increased however by adopting certain methods :—

There is still a great deal to be learnt about the exact nature of fixation in different types of soils, its significance in relation to phosphate ability, and its bearing on the types of phosphate fertilizers to be used, together with the best ways of applying them. It is important to appreciate that information obtained from experiments on one type of soil does not of necessity hold for other types,

nor does the information obtained in one country necessarily apply in another where climatic and other conditions are different.

It seems likely that the supply of phosphates will be one of the key problems in the agriculture of the future, and there is no easy solution of the numerous difficulties associated with it. Unlike nitrogen, phosphate cannot be fixed from the air, nor can it be extracted from certain seas and lakes as is potash from the Dead Sea at the present time.

### ORGANIC MATTER IN RELATION TO SOIL FERTILITY

The continued debate on the value of organic manures in different systems of farming arises from the difficulty of analysing the dominant factors in particular cases. In considering physical effects it is necessary to distinguish the coarse organic material still retaining its structure from the fully rotted colloidal material. Gross mechanical effects are important in opening up heavy soils. For this purpose long manure and even straw may be applied. Long manures may leave light land too open and well-rotted ones are therefore preferred at the cost of more loss of plant nutrients.

The rotting of straw and sewage sludge together, either in compost heaps or in the soil, may add to the humus supply and provide the three principal plant nutrients, if the necessary conditions can be worked out. The well-rotted organic material enters into intimate association with the inorganic colloids and provides a large part of the soil's base exchange capacity, i.e. improves its power of holding potassium, calcium, magnesium in active and available forms. The organic colloids help to stabilize the soil crumbs and increase the capacity for air and water.

**The Maintenance of Soil Organic Matter.** An adequate amount of organic residue must enter the soil at frequent intervals. This alone may not maintain the soil humus at a desirable level or give the rate of energy release and end-product formation most favourable for crop production. The nitrogen of the soil organic matter is closely correlated with and exerts a marked control on the amount of humus that results.

Nitrogen and calcium are concerned in the rate of decomposition of organic matter. Unless both of these elements are present in suitable amounts, the turnover of the organic matter will be too

slow. In short, the problem is threefold—sufficient organic residues, enough nitrogen to assure a high level of humus accumulation, and adequate calcium with the nitrogen to promote a biological activity that will keep the organic matter cycle in full swing.

Carbon, nitrogen and lime tend to stimulate organic decomposition and promote a release of energy and a formation of end-products favourable for higher plants. For example, as long as the nitrogen-carbon ratio is wide, nitrates will not accumulate since the nitrogen is used by the rapidly multiplying organisms and higher plants may thus be subject to a serious nitrogen shortage. But with a rapid turnover this period of excess carbon is soon over, the nitrogen-carbon ratio narrows, and conditions that will admit nitrate accumulation are promoted.

The liberation of nutrients, however, depends largely upon biological processes and also upon the solvent effect of strong acids. The greatest quantity of water-soluble nutrients is found in the surface soil where organic matter is abundant and where biological processes are most active.

#### SOIL NITROGEN, POTASSIUM AND CALCIUM IN RELATION TO SOIL FERTILITY

**Soil Nitrogen.** The presence in the soil of an adequate supply of available nitrogen is one of the most important factors relating to the maintenance or improvement of soil fertility. The lack of sufficient amounts of available nitrogen in soils, particularly those that have been cropped for many years, has long been a limiting factor in crop production. A deficiency of available nitrogen results in plants of poor colour and appearance, poor quality, and low production. A sufficient supply of available nitrogen, on the other hand, is largely instrumental in getting plants off to a quick start and has a subsequent tendency to encourage stem and leaf development. Such plants will make a more rapid, thrifty growth and possess a normal deep-green colour and generally healthy appearance. It has been shown also that plants supplied with sufficient nitrogen are much better able to utilize other nutrient materials such as phosphorus and potassium compounds. The curtailed leaf surface resulting from a lack of available nitrogen in the soil is usually reflected in a lowering of yield, since yield is ordinarily proportional

to leaf development. No amount of available phosphorus and potassium will overcome a deficiency of available nitrogen ; it is generally recognized that one nutrient element cannot be substituted for another. An oversupply of available nitrogen in the soil, on the other hand, tends to cause late maturity and poor seed development and to make plants more susceptible to disease organisms on account of the development of more succulent tissue, and is decidedly uneconomical because of the unnecessary use of soil nitrogen above actual plant requirements.

**Maintenance of the Supply of Nitrogen in the Soil.** Of all the nutrient elements nitrogen is probably the most necessary to supply and certainly the most difficult to regulate. The control it exerts on the soil humus, its ready loss in drainage, its complicated transformations, and its notable influence on crops makes it an element of outstanding interest and attention. Once the nitrogen problem is solved, the other factors concerned with fertility maintenance are more readily amenable.

That the upkeep of nitrogen is critical is not difficult to demonstrate. Assuming that drainage and volatilization losses of nitrogen are offset by rainfall and azofication, the removals by the harvested crop and by erosion are left unmet. This deficit in a general way probably amounts to at least 75 pounds of nitrogen an acre a year. Such a loss is equivalent to approximately 470 pounds of commercial nitrate of soda. A deficit of this magnitude must be cancelled at least partially in order that the productivity of the soil should remain at a profitable level.

Of first importance in nitrogen control are crop residues, not only the above-ground parts but the roots as well. By those means a considerable amount of nitrogen is continuously returned in organic form. As decay, ammonification, and nitrification takes place, this nitrogen again becomes available to higher plants. Such returns are more or less automatic and greatly reduce the difficulty of meeting the yearly nitrogen deficit.

Contrary to common belief there is no justification for cutting down the nitrogenous dressings merely because a crop has been dunged. Dung improves the physical conditions and supplies many nutrients which allow the crop to respond to further dressings of inorganic nitrogen. In some quarters there is still a prejudice against nitrogenous fertilizers because they are alleged to exhaust the soil. Certainly bigger crops take more out of the land, but

few farmers object to good weather, good seeds, and good cultivation because they, too, give bigger crops.

The use of a legume as a regular harvested crop of the rotation is also important in the maintenance of soil nitrogen. With legumes such as clover, lucerne, and vetch, the amount of nitrogen removed in the harvested crop may be equalled by that gained by nodule fixation. It is thus possible to grow and remove such a crop with little or no draft on the soil as far as the nitrogen is concerned. Such a possibility is extremely important in any scheme of nitrogen conservation and maintenance. Legumes, however, have been and probably will continue to be the principal source of nitrogen in arable soils that the farmer controls. Leguminous plants, therefore, are the foundation upon which agriculture rests and upon which man is markedly dependent.

Legumes, however, vary greatly in their efficiency in fixing nitrogen ; eighty pounds per acre may be used as a conservative figure for the average annual fixation of nitrogen by legumes. According to Mehring, the commercial manufacturing plants for the fixation of nitrogen in the United States produced 200,000 tons in 1938. Their rated capacity is 340,000 tons, or 680 million pounds, of nitrogen annually. The production figures seem large ; yet they represent only about  $\frac{1}{2}$  pound an acre a year for the combined crop, pasture, and range land in farms in the United States.

As previously stated, 80 pounds of nitrogen an acre a year is a conservative estimate of the average yearly fixation by legumes. At this rate of fixation, 5 million acres of average leguminous crops fix a quantity of nitrogen equivalent to the total annual production of electrically fixed nitrogen (1938) in the United States. This acreage of legumes is less than one-twentieth, or 5 per cent. of the area of legumes that good soil-management practices demand. From these figures, it is clear that, if legumes were grown regularly in the 4 year rotation on American farms, these legumes might fix twenty times as much nitrogen as was produced by commercial electrical processes in 1938. The use of legumes to their full capacity in rotations of 3 to 5 years and, in addition, the full use of the commercial factories for the fixation of nitrogen for vegetables and special cash crops should help farmers to maintain the supply of nitrogen in the soil. Such additions to the soil would aid in balancing the annual outgo of nitrogen, and balancing it is essential to a permanent agriculture.

It is only fair to suggest that commercial nitrogen is used in general and dairy farming primarily to supplement the nitrogen already present in the soil and not permanently to increase its amount. In fact, the crop is usually so stimulated by the narrower nitrogen-carbon ratio that it not only uses the nitrogen added in the fertilizer but more of the soil nitrogen than it probably otherwise would. Fertilizers thus seem to be less important in the maintenance of soil nitrogen than are farm-manure, crop residues and legumes. With vegetable growing on sandy soil, the situation is different. Here the main reliance is placed on commercial fertilizers, the soil functioning more as a medium for than as a source of nutrients.

**Soil Potassium.** Inasmuch as soils are produced by the breaking down of rocks by the process of weathering, all soils contain potassium in the potash-bearing constituents, such as feldspar, occurring in these rocks. Investigators time and again have shown that practically all the potash minerals originally present in rocks are found as such in arable soils. As the potassium in such minerals becomes available or as potassium salt is added to the soil in the form of fertilizer, crop plants utilize its compounds as is evidenced by an analysis of their ash, in which the potassium is found principally as potassium carbonate, although occurring in the living plant in both organic and inorganic combinations. Since human beings and animals of all kinds obtain their food supply directly or indirectly from plants, it is not surprising that potassium is found in all animal tissues and secretions, such as muscles, blood, urine, albumen, eggs, milk, hair, etc. The dependence of all life upon potassium is, therefore, as self-evident as is the case with nitrogen or phosphorus.

**Quantity of Potassium in Soils.** Unlike nitrogen and phosphorus the quantity of potassium found in soils is comparatively high. A mineral soil with a nitrogen content of 0.2 per cent.—about 4,000 pounds of nitrogen in 6 or 7 inches of top-soil—is considered to be well supplied with this particular element, and the same applies to phosphorus. A soil with only 0.2 per cent. of total potassium would be rated very low in this element. There are some cultivable soils, such as sands and light sandy loams with pervious subsoils, and mucks and peats, which are generally not only very deficient in available potassium but quite low in total potassium. It is such soils that give the most striking response

to applications of available potassium in fertilizers. The ordinary range of potassium expressed as the oxide ( $K_2O$ ), in the upper surface of mineral soils will range from 0.15 per cent. in sands to 4 per cent. and over in clay soils. Taken as a whole, however, the general run of soils contain fairly large quantities of potash, averaging approximately 2 per cent. This means about 40,000 pounds of potash in the plough layer whereas nitrogen will hardly exceed 4,000 pounds and phosphoric acid 3,000 pounds. It is important to consider, however, that even with such a large reserve of potash in soils it is generally present in relatively insoluble compounds.

The annual acre loss of potash to the average crop and to drainage combined, amounts to possibly 125 pounds as a maximum. In terms of commercial muriate of potash this equals 250 pounds which seems a large yearly removal. Yet compared with the total potash in the soil it is insignificant. Obviously the potash problem of the average soil is not a question of totals but of availability.

The soil potash situation is somewhat anomalous. Large amounts of this constituent are being carried away by drainage water and yet a crop growing on the soil may benefit from a potassium fertilizer. Apparently adequate absorption by higher plants will not occur until there is a wasteful sufficiency of potassium in the soil solution. A mobility of this constituent rivalling that of calcium is constantly demanded.

If the organic matter, nitrogen, and lime are maintained at an adequate level in the soil, the solvent action of the carbon dioxide will be at its maximum and perhaps potassium solubility lavish enough to meet the needs of higher plants will result. This seems to be the case with many virgin soils. The maintenance of soil organic matter, therefore, may automatically solve the problem for the heavier soil where the total content of potash is high. On arable soils the application of farm-manure in addition to the usual organic residues has been found most helpful. Ten tons of average manure supplies about 100 pounds of potash, equivalent to that carried by 200 pounds of commercial potassium chloride. Up to the present time the potash problem of most soil has been met in this twofold manner. Now, even the heavier lands are beginning to show an acute need for potassium fertilization.

With light soils the situation is different. Here the potash is low and with many crops this element must be added artificially. While farm-manure and crop residues contain potassium, such

sources are usually inadequate on sandy soils and commercial fertilizers must be relied upon.

In natural conditions, however, supplies of potassium may be adequate for low levels of nitrogen or phosphorus supply, but inadequate for higher levels. Signs of potash starvation may therefore set in when nitrogenous or phosphatic fertilizers are given without potassic fertilizers.

**Soil Calcium.** There can be no doubt that the principal cause of infertility in soil throughout temperate countries is shortage of lime or, what comes to the same thing, soil acidity. Drainage water necessarily carries away lime, mainly as calcium bicarbonate. The loss is greatest in the wettest regions or where the rain is acidified by sulphuric acid from coal fires and industrial plants. It becomes serious most rapidly on light soils or on those derived from rocks of low base contents.

**The Utilization of Lime.** Three practical questions must be answered in respect to lime. Is lime necessary, and if so, what kind shall be applied and in what amounts to the acre? These queries have already been so fully considered (*see* chapter 12) that only two points in respect to liming need be re-emphasized.

First, while lime is often spoken of as a soil amendment, its major benefit is probably nutritional. That is, the calcium and magnesium really function as fertilizer elements, the indirect influence serving to augment and intensify the direct effects. And second, lime is not to be used carelessly as a cure-all but applied judiciously or not at all. Too much lime or lime for the wrong crop is just as bad as the failure to enlist its benefits when they are possible.

**Plant Growth—Substances in Soil.** In 1938 Bonner and Greene investigated the vitamin B<sub>1</sub> content of three samples of cattle dung and found them to contain about 0.1 mg. per kg., but a laboratory culture of *Azotobacter* contained over a thousand times as much. However, the first demonstration of the presence of a growth-substance in soil was the detection of vitamin B<sub>1</sub> by Lilly and Leonian, using a biological method, in 1939. They tested William and Spie's theory, that thiamin (Vitamin B<sub>1</sub>) may be present in soils by growing certain thiamin-requiring fungi. Even the fourth foot of soil was found to contain sufficient thiamin to induce fair to good growth.

Parker-Rhodes has provided evidence of the existence of indole-

acetic acid and similar substances in concentrations of the order of 0.1  $\mu\text{g}$ . per kg. of dried soil unmanured or manured with artificials, and about double that amount in soil receiving farmyard manure in unspecified time previously ; he has also investigated the effect of soil sterilization on the heteroauxin content.

A heteroauxin is defined "as any aryl-substituted lower fatty acid which has been shown to be active in at least one of the recognized tests for growth-promoting activity." The definition excludes the two true auxins—auxin-a and auxin-b—otherwise known as auxentriolic and auxenolonic acids. It also excludes the vitamins, of which at least one—known variously as vitamin B<sub>1</sub>, aneurin, and thiamin—when applied artificially to plants has potentially manifested growth-stimulating effects similar to those produced or evoked by the auxins and by heteroauxin itself (indole-3-acetic acid) and the numerous synthetic aryl-substituted lower fatty acids identical with or chemically akin to the latter.

The availability of certain elements in the soil effects these plant growth-substances to a great extent. J. Hester has showed, for instance that the content of ascorbic acid in tomato fruits increases with increase of available manganese.

### POSSIBLE STIMULATING EFFECTS OF RADIUM EMANATIONS

Rocks and soils contain measurable amounts of radio-active substances : the following are usual quantities found per gram :—

TABLE 57

	Radium grms.	Thorium grms.
Sedimentary rocks ... ..	$1.4 \times 10^{-12}$	$1.6 \times 10^{-5}$
Basic rocks (basalts) ... ..	$1.19 \times 10^{-12}$	$0.8 \times 10^{-5}$
Acid rocks (granites) ... ..	$3.34 \times 10^{-12}$	$2.81 \times 10^{-5}$

Moreover, the potassium compounds of the soil are radio-active (emitting, however,  $\beta$ -rays only), and owing to the large amount their total activity is comparable with that of radium and thorium. All these emanations have stimulating effects on plant growth.

## ELECTROCHEMICAL RELATIONS BETWEEN THE ROOT SYSTEM AND THE SOIL

By potential measurements on cereal roots H. Lundegardh showed that the root surface is negatively charged (50-60 millivolts in ordinary culture solutions). This negative charge is the cause of the strong cation absorption on roots. He considers that the determining factor in root nutrition is the speed with which ions can be supplied to the root surface from the colloidal particles. This depends on the physico-chemical properties of the ions, their electric charge, degree of hydration, etc. There is no evidence, however, that ion absorption by roots is impeded by a "counter-pressure" exerted by soil colloids.

Lundegardh, however, devised a method for determination of the potential differences between the soil and the root system of plants in pots. He put forward a theory of the electrochemical properties of the surface of living roots, and extended it to the boundary between the roots and the soil. Implications of the theory include the possibility of using the determination of P.D. for the control of fertilizer experiments and the investigation of the free acidity of different types of soil.

## SOIL NUTRITION

Some workers recently suggested that a new branch of soil science be recognized, namely, soil nutrition. Soil nutrition would be related to general pedology, or soil science, in much the same way as plant nutrition is to botany or animal nutrition to zoology.

Most soils possess an almost limitless supply of the major and minor plant nutrients (and toxins) and, when properly nourished, give them up to, or withhold them from, the vegetation in the quantities required for normal plant growth. The mechanism of this remarkable process should be the subject of the soil nutritionist's study.

Soil nutrition may not be of much practical importance in agriculture, where plant nutrition is becoming increasingly independent of the soil, but it is fundamental to the science of the soil.

### THE USE OF CHEMICAL ANALYSES AND TESTS IN THE DETECTION OF FERTILITY DEFICIENCIES

In dealing with the fertility needs of any particular soil it is necessary to know, first of all, what nutrient element or elements are deficient. In the popular mind this appears to be a very simple proposition. Chemical analyses are so common that it would seem mere routine to analyse the soil for the various nutrient elements and immediately detect the constituents limiting crop growth. Not only this, but the analysis, in the public mind, is supposed to indicate the amount of fertilizer that should be applied to rectify the difficulty. No phase of soil science has received as much popular recognition as chemical analysis, nor is any other technical soil procedure so little understood in general and at the same time so greatly overrated.

In the total analysis the entire amount of any particular constituent present in the soil is determined regardless of its form of combination and its mobility. Such data are of great value in the scientific study of soils and little progress in pedology would have been made without this type of analytical results.

In spite of the great importance of total analyses in soil research and teaching, they fail entirely in one very important respect. No hint is given as to the availability or non-availability to plants of the constituent under consideration. And this, of course, is the vital question in fertility decisions. Unless an element is sufficiently mobile, it is sure to be a fertility liability. Thus a soil high in total nutrients may respond to a commercial fertiliser, while one that is much lower may require no such accession. As a result, total analyses are all but valueless in making practical recommendations.

Partial analyses are of many kinds. At one time it was considered feasible to digest the soil with a weak acid of just such strength as to remove the nutrient, or nutrients, that would, under field conditions, be immediately or at least rather easily available. Such a method is so arbitrary and artificial, and leaves out of consideration so many important factors, that it has been impossible to correlate data so obtained closely enough with crop response to be of use in a practical way. As a consequence, this type of chemical analysis is now practically abandoned.

At present, determinations of the amounts of replaceable calcium, magnesium, potassium, and other elements are being used to further

our knowledge of the chemical organization of soil colloids. These analyses are, of course, partial in nature, as only small proportions of the important nutrients are held in an exchangeable condition. Since such constituents are mobile and therefore probably available to plants, determinations of this nature may in time become of practical value, especially if they can be standardized and correlated with crop response. Although the degree to which the soil colloidal matter is saturated with a particular cation is known to have a great influence on physiological conditions, the practical interpretation of such analytical data is as yet very difficult.

Finally there are the rapid tests which are now greatly in vogue and are so widely advertised. Some of these are undoubtedly of great value, while others may in time be abandoned. The determination of pH and the Comber test, unquestionably, have merit in the control of soil acidity and the factors associated with it. As a basis for lime recommendations they are both of practical value.

Of the other rapid tests it is not possible to speak with such assurance. At best they give only a rough idea of the amounts of easily available constituents present in any soil, as they are arbitrary and artificial, like all partial determinations. Those for phosphorus, calcium, magnesium, manganese, and aluminium seem most promising. Their interpretation is, of course, the stumbling-block as it requires not only a practical knowledge of the crop to be grown but also an understanding of the soil type under consideration. Soils that give the same test with a given reagent may respond quite differently to the same fertilizer treatment in the field. It is not only futile but also dangerous to place tests in the hands of amateurs.



## *Soil Conservation*

BY soil conservation is meant the maintenance of the fertility of the soil and saving it from erosion.

Soil erosion is the removal of the top fertile layer of the soil either by high winds, heavy rains or a combination of these two factors. It is liable to occur in any region where the soil does not easily cover itself with vegetation, or where the vegetation cover is deliberately removed and kept off. It is not common in temperate countries because so much of the land is in grass, and because, on the remaining land, there is usually a crop either of sown plants or of weeds. But in dry regions where a vegetation cover is not easily maintained erosion is very liable to occur, especially as the rain, when it comes, is apt to be torrential. Several inches of rain may fall in one day. The problem is really an ancient one, as is shown by the terraces set up in the Mediterranean countries for the purpose of saving the soil from the losses that would otherwise occur.

Soil erosion has actually been going on since the world began. If it were not that the heavy rains at the source of the rivers washed fertile soil into them, river valleys would not have possessed all those rich and fertile lands where this soil has been deposited throughout the centuries. Again this is the reason why, all the world over, valleys are more fertile than the hill sides surrounding them because the soil is enriched in the former at the expense of the latter.

Through the ages, soil erosion has exerted a tremendous influence on the course of civilisation. History is largely a record of human struggle to wrest the land from nature, because man relies for sustenance on the products of the soil. Yet, only too frequently, man's conquest of the land has been disastrous; over extensive areas his culture of the earth has resulted in extreme impoverishment or complete destruction of the soil resources on which he is dependent. So direct, in fact, is the relationship between soil erosion, the productivity of the land and the prosperity of a people,

that the history of mankind, to a considerable degree at least, may be interpreted in terms of the soil and what has happened to it as a result of human use.

People treat the soil as though it were a mine and, like a mine, it eventually becomes exhausted. That is not the real purpose of the soil. Soils should be treated in a reasonable way. We should give back to it some of what has been taken from it. In Europe and other parts of the world, notably in China and Egypt, people have been cultivating the soil for more than four thousand years. They used to return to the soil the greatest possible amount of animal and plant residues. The Chinese utilise up to the present day these residues by making up composts of all the waste vegetable matter that they can obtain together with human and animal excreta. This is one of the most important manures which for long has been used in China.

The menace of soil erosion is spread over many areas throughout the world. Every country has started to tackle the problem. In the U.S.A. many efforts are devoted to this kind of work. A new department called the Dept. of Soil Conservation was set up under the American Ministry of Agriculture.

The U.S.A. is probably one of the countries which has suffered most heavily from soil erosion. The pioneers found wide areas of land available for cultivation. They used to overgraze those soils until they became exhausted. Many of the pastures were transferred into arable land and thus the upper layers of the soil were exposed to erosion. H. H. Bennett has shown that in the South-Eastern United States, Cuba, and Central America, soils fall into two classes with respect to their liability to erosion. On the one hand, soils whose clay constituent is characterized by excess of sesquioxides are markedly resistant to erosion, probably owing to their tendency to assume a crumb structure, which favours the rapid adsorption of a rainfall. On the other hand are soils whose clay is of a more siliceous type. These are more readily eroded owing to their tendency to deflocculation.

The extent of erosion in the tropics and certain parts of the sub-tropics is very intensive. A measure of its intensity is furnished by the content of suspended matter in river waters. Whilst in the rivers of Western Europe this amount is generally less than fifty grams per cubic metre, from 2,000 to 10,000 grams per cubic metre are found in tropical rivers.

We may mention in that respect that it is feared that erosion will increase in Russia as a consequence of the present war.

**Factors Affecting Soil Erosion.** Erosion and erosion losses are not due to one or even to a limited number of causes, and no one remedy or preventive measure can be regarded as a panacea. In checking erosion, a thorough diagnosis is necessary before proper preventive remedies can be prescribed in order to correct the existing conditions.

Why erosion started is a very complex affair but the principles underlying erosion are essentially simple. It began when the first heavy rain struck the first furrow turned by a crude implement of tillage in the hands of prehistoric man. It has been going on ever since, wherever man's culture of the earth has bared the soil to rain and wind.

Soil erosion is not to be confused with geological erosion which, as part of the complex process of rock weathering, is essential to the formation of soil and aids in its distribution from place to place. Geological erosion takes place in a natural and undisturbed environment where vegetation, with its stems, ground cover of litter and underground network of binding roots, retard the transposition of surface soil by wind or rain to a pace no longer rapid.

Soil erosion, on the other hand, is a vastly accelerated process brought about by human interference with the normal equilibrium between soil building and soil removal. Where the land surface is bared of protective vegetation, as it must be under cultivation, soil is exposed to erosion because the various plant residues which rot in the soil act as a sort of glue which aids in the cohesion of the soil particles. Transposition processes of an extremely rapid order are set in motion and soil is bodily displaced much faster than it can be formed. Unless adequate measures are taken to guard against this abnormal removal of the top fertile layer of soil it becomes the most potent single factor contributing to the deterioration of productive land.

It is obvious that, where considerable erosion occurs, the natural soil profile is destroyed or truncated and, indeed, may never attain full development. In considering the relationships of the soils of a particular region to the great soil groups, it is therefore necessary to make allowance for the possible effects of erosion in the past. This is particularly the case in humid tropical and sub-tropical regions, where erosion is intense and has led to considerable modifications in profile development.

## TYPES OF EROSION

Water and wind are the active forces of soil erosion, differing in the nature of their action and in outward manifestation, but similar in the sense that both remove and transport surface soil. Both represent major problems having to do with land defence and preservation. This erosion can be divided into two main types :—

(A) Water Erosion. (B) Wind Erosion.

(A) *Water Erosion.* Water erosion is the transposition of soil by rain water, including melting snow, running rapidly over exposed land surfaces. It is conditioned by factors of slope, soil type, land use and intensity of rainfall and is confined to sloping areas, where the land is of a kind susceptible to washing and where land-use practice has stripped the surface of the protective vegetation. It is a progressive process, aggravated by cultivation and over-grazing and sometimes by burning. In general it may be divided into 3 types which, while closely related, are by no means mutually exclusive. Two or more of them may occur simultaneously in the same field ; one may develop into another. For the purpose of discussion, the general category of water erosion may conveniently be sub-divided into :—

- (1) Sheet Erosion
- (2) Rill Erosion
- (3) Gully Erosion.

(1) *Sheet erosion.* Sheet erosion is the more or less even removal of soil in thin layers over an entire segment of sloping land. It is the least conspicuous and the most insidious. Unprotected land varies widely in its susceptibility to sheet erosion, the differences depending on the degree of slope, climate environment, and character of the soil. H. H. Bennett reports a 25 per cent. increase in erosion for each 1 per cent. increase in gradient over 1 in 27 on a loam soil in Missouri.

(2) *Rill erosion.* In some cases the surface water, instead of flowing evenly over a sloping field, generally tends to concentrate in streamlets of sufficient volume and velocity to generate cutting power. The result of this form of running water is rill erosion, which, in contrast to sheet washing, is characterized by small incisions left in the land surface by the cutting action of water.

(3) *Gully erosion.* Gully erosion takes place either where the concentrated running water from a bare slope increases sufficiently

in volume and velocity to cut deep incisions or gullies in the land surfaces. Usually gullies follow sheet erosion or result from the neglect of rills. Frequently they have their beginning in slight depressions of the land surface where running water normally accumulates.

(B) *Wind erosion.* Erosion by wind presents a problem of gravity equal to that of water erosion. Often it occurs in areas where water erosion is also active, but in any one locality the two types rarely assume an equal degree of importance. Soil washing attains its most serious proportions on land with a considerable degree of slope and an intensive rainfall.

Unlike erosion by water, wind erosion is not easily divisible into forms or sub-types. One example of soil blowing ordinarily differs from another in degree rather than in kind. In severity, however, wind erosion may range all the way from a slight disturbance of the surface soil over a small area to the huge dust storms that sweep across vast areas, remove countless tons of soil, and constitute a major catastrophe.

Early in 1937 a dust storm which originated in Texas, in the U.S.A., travelled across five states and on into Canada. The dust was carried a distance of more than 500 miles.

When the grass cover is removed by ploughing, the original stability of the soil is greatly reduced. Cultivated soil, depleted of the binding effect of grass roots and of the spongy organic matter which normally accumulates under a cover of grass, becomes less cohesive.

Soils vary considerably in their resistance to wind erosion, depending generally on their structure, the size of their particles and their content of organic matter. Neither coarse sands nor heavy clays are immune. ✓✓

The action of wind, as well as of water, upon the soil is something like that of a sieve. Wind picks up the lighter, more fertile soil particles and lifts them into the pathways of high air-currents, which often carry them for hundreds and sometimes thousands of miles.

Wind erosion, at the present day, is principally active in desert and semi-desert regions. Since only the finest particles are liable to transport by wind it frequently happens that a sorting out occurs whereby fine material is removed and the coarser gravel and stones remain behind as "desert pavement." This effect is only operative

at the immediate surface and finer-grained material is found below the level of stones and gravel.

The occasional occurrence of hard layers of calcium carbonate at the surface in parts of the South African Karroo and other deserts may be due to removal of formerly overlying layers by wind action.

#### **Equilibrium between Soil Formation and Soil Erosion.**

The earth is continuously discarding its old worn-out skin and renewing its living sheath of soil from the dead rock beneath. In this way equilibrium is reached between denudation and soil formation so that, unless the equilibrium is disturbed, a mature soil preserves a more or less constant depth and character indefinitely. The depth is sometimes only a few inches, occasionally several feet, but within it lies the whole capacity of the soil to produce life.

The accelerated erosion of soil taking place as a result of unwise cultural practices, has had increasingly deleterious effects on the physical body of the land. Within the past century, it has made cultivation economically unsound : for a long time to come, at any rate, it has narrowed the potentialities of agriculture and limited the area in which it may be practised successfully.

In America alone, water and wind erosion together remove yearly not less than 3 billion tons of soils from the croplands and associated pastures. Some 730,000,000 tons of solid matter are carried annually into the Gulf of Mexico by the Mississippi River alone.

These 3 billion tons of wasted soil contains the equivalent of some 90 million tons of phosphorus, potassium, nitrogen, calcium and magnesium. Of this, 43 million tons represents phosphorus, potassium and nitrogen, the principal ingredients of commercial fertilizers.

No other process or combination of processes, is so destructive of valuable soil and its nutritive constituents as erosion. More important than the loss of plant food-constituents through erosion, however, is the loss of soil itself. Erosion removes the entire physical mass of the soil, the mineral particles, the plant nutrients, the beneficial microscopic organisms, and all other constituents, in other words, the whole body of the soil itself.

Crops remove only selected parts of the soil, i.e. the immediately soluble constituents upon which they feed. Thus, while crops impoverish the land, they extract only diminutive portions of the

soil, leaving the bulk of the material which may be subsequently improved with manures and soil building crops. Erosion, if not checked eventually takes all, leaving nothing to be improved.

**The Effect of Erosion on Soil Organic Matter.** A correlation has been shown between the decrease in organic matter content of a series of plot soils, and the amount of erosion that occurred in some parts of the United States. Determinable depletion occurred only at the higher erosion rates. This circumstance leads to the inference that many reported depletions of organic matter, formerly attributed to oxidation, may have been erosional effects.

In the soils examined, depletion of organic matter appeared to be a linear function of erosion. The organic matter percentage of the soil dropped 0.002 per cent. at both the Clarinda and Bethany stations for each ton of soil lost by erosion.

It is shown that the amount of organic matter removed by erosion is greater than the corresponding depletion indicated by analyses of the plot soils, consequently, restoration to an original organic matter level does not compensate for losses of "reserve" organic matter.

For a fallow plot on which the greatest erosion occurred, it was estimated that erosion had increased the depletion of organic matter to eighteen times that normally lost by oxidation, and that to maintain the organic matter at the original level it would be necessary to apply as much as 9.2 tons of clover hay annually.

In some other experiments, contents of organic matter, N, P, K and Ca in eroded material were respectively 4, 4, 1.5, 1.4, and 2.3 times those of the soil. Taking potato yields on areas having less than 3 inches of surface soil as 100, yields from areas having 3-6, 6-9 and over 9 inches of surface soil were 110, 119 and 129 respectively.

The eroded material in most cases contained from three to eight times as much nitrogen and organic matter as did the soil itself. The amounts of organic matter and nitrogen in the eroded material were affected by the intensity of the rainfall and by plot treatment. There was evidence of selective erosion of certain fractions of the organic matter.

#### METHODS OF SOIL CONSERVATION

Three stages have usually marked the opening-up of a new country in recent times—(1) the soil-erosion stage ; (2) the anti-

erosion stage ; and (3) the soil-conservation stage. There will doubtless be further stages of development arising out of (3) as time goes on, but hitherto very few of the newer countries have reached even the third stage. Most have passed the first and are now in the second. In neither of these two has a country much opportunity for displaying its individuality ; erosion looks about as ugly in one place as in another, and the forces that must be brought into operation to stop the movement of loose mineral deposits are also much the same everywhere. The third stage, however, is concerned with the positive building-up of soil fertility and it is in this stage that the people of a country must show its character, since every part of the world possesses unique measures for their improvement.

Perhaps the only " new " country in which stage (3) is really under way is the United States where, of course, erosion is still going on and still being stopped but where, nevertheless, interest is clearly shifting from erosion-stopping to soil-building.

In discussing the various measures to be taken in checking soil erosion it is best to divide erosion into two main types, namely, " vertical " and " lateral " erosion. In distinguishing between those types we would say that the former involves the washing and removal by leaching from the soil of all soluble salts and plant nutrients, and the latter involves mainly the washing or blowing away of the insoluble parts. " Vertical " erosion is always liable to occur in humid regions. Lateral erosion is very liable to occur on unprotected soils in arid regions because when it dries out the soil pulverizes and loses its water-absorbing power. Both " vertical " and " lateral " erosion occur in the humid tropics owing to the effects of extreme heat and torrential rain.

The technical problem of preventing " vertical " erosion in soils under cultivation has been solved by manuring and by ploughing, harrowing, rolling and so on, with the object of keeping soil moisture near the surface. These cultural practices were originally adopted because they were found to produce good crops and to keep the soil in good heart. It did not enter the farmer's head that by tilling the soil he was recompensing it for the loss of protection against " vertical erosion " afforded by natural vegetation. He probably recognised the importance of keeping the plough layer moist, but soil chemistry was a closed book to him. Nevertheless he managed to avoid the main dangers of washing out plant nutrients

resulting from vertical erosion, as successfully as if he had possessed the knowledge of soil chemistry now available.

Agriculture, however, has its beginnings in arid lands where precautions against "vertical" erosion were unnecessary. Indeed, in the very arid plains, irrigation was used actually to induce some "vertical erosion" and to remove the excess of soluble salts as well as to supply water for crops.

The principles of soil conservation that will have to be introduced in checking "lateral" erosion are fundamentally the same as those which evolved naturally as part of the agriculture of the Ancient East, but they will have to be profoundly modified in detail to suit the changed conditions of modern Agriculture. The first object of soil conservation is to make the best use of rain. When this is achieved, the problem of preventing lateral erosion by either water or wind is already half solved.

The first principle underlying all measures for controlling water erosion is to reduce the velocity and amount of water running on the surface of the soil. This water is often referred to as "run-off." One of the most common methods of reducing the velocity is to break a slope by terracing. Damming water courses is a purely mechanical way of checking run-off. By throwing a dam or a terrace across the direction of flow, run-off water is held up, soil carried in suspension is deposited, and by skilful management any excess of water not absorbed by the soil may be turned to some useful purpose such as irrigating lower-lying land or watering stock.

Erosion on terraced and unterraced fields on volcanic soil at 1,800 m. altitude on Java was compared. There was little erosion on either area the first year after felling the virgin forest, but it increased as the humus diminished. In the second year erosion from unterraced fields amounted to 5 kg. per sq.m., twice as much as that from terraced fields.

**Biochemical Control of Soil Erosion.** Nowadays, however, a diminishing importance is being attached to the mechanical conservation of the soil. An outstanding feature of the modern outlook on soil conservation is the emphasis laid on the superior value of biochemical, as compared with mechanical, erosion control. If the soil is performing its natural biochemical functions, i.e., its functions of feeding plants which maintain a great number of living micro-organisms, it will not in general erode seriously.

Biochemical control of erosion by means of plants may be likened

to treating a disease by dieting or to maintaining good health by temperate living. Mechanical control may be likened to a cure by operation.

The main biochemical or biological measure of soil conservation is the protection of the soil surface by a vegetal cover, be it crops or trees. Nature's method of protecting the land surfaces by a mantle of vegetal cover has, of course, been highly successful, perhaps it was not realized just how effective such a cover could be until recent studies showed the great difference in measured losses of soil and water from land under grass and from land cultivated with crops. These studies showed that the rate of loss was such that it would require only 56 years to erode 7 inches of surface soil when the land was in arable condition, but more than 3,500 years when the land was in permanent grass.

Many studies have been undertaken on many different soils and land slopes and in regions having different rainfall characteristics. These have shown without exception very wide differences in soil and water losses from cultivated land and from land under a protecting mantle of close vegetation. Probably one of the important ways in which close vegetation protects the ground surface is through the interception of some rainfall by the plant surface in the same manner in which a dense forest prevents much of the rain from reaching the ground surface. Another important effect of close vegetation is that of protecting the soil surface from the beating action of dashing rains which normally cause surface water to become very muddy.

Where arable farming is concerned, soil conservation with crops consists in cultivating in such a way that as much of the soil as is practicable is protected by plants for as long as possible. Hence the bad name, that widely spaced, clean tilled crops like cotton, maize and tobacco have gained from the erosion that so frequently accompanies their culture. With such crops, some measure of mechanical soil conservation is often unavoidable. With some clean-tilled crops the soil can be adequately protected by allowing weeds to grow. Weedy land is no longer necessarily a sign of bad farming. The rubber tree, whose natural habitat is the tropical rain forest, grows just as well on weedy as on clean land. For many years it has been the custom in Malaya and Ceylon not to trouble much about weed growth in rubber plantations.

Instead of protecting the bare spaces between crop plants with weeds of no economic value, useful cover should often be grown.

This method is very advantageous. Leguminous cover crops which fix atmospheric nitrogen actually enrich the soil and are especially valuable. Cover crops, of course, may compete with the main crop in the same way as weeds, but on the other hand, if judiciously selected, may actually increase the vitality of the main crop, since many plants are subsequently ploughed back as a green manure, and the soil is improved when the added organic matter rots.

In semi-arid countries, such as many of the countries bordering on the Mediterranean, it would be a good policy to use suitable rotations as a measure against erosion. The essence of soil-conserving rotations is to alternate arable crops with dense sod crops, the function of the sod being not only to protect against rain and wind, but also to build up the soil structure and to make the soil more resistant to erosion when next it comes under the plough.



## CHAPTER 25

### *Soils and Agriculture*

EARLY man was a ranging nomad, constantly changing his abode from landscape to landscape, always in search of new hunting grounds or fresh pastures. Great nomadic kingdoms grew upon the grasslands of central Asia, but they had no stability, no roots, and left few marks on the pages of world history and certainly less on those of civilization ; they accomplished little of importance until they settled down—ceased to be nomadic.

The birth of primitive agriculture was the birth of civilization, and with it there came a great change. As a farmer, man himself became closely attached to the landscape, firmly rooted to the soil that supported him.

Soil is the natural medium for the growth of plants. Although most soils are produced from weathered rocks, the rain and the sun have changed them greatly. Of still more importance are those changes made by the plants themselves. Thus soil is made through the influence of both physical and biological forces. It is especially the biological forces that give those characteristics to a soil or landscape that are most important to man. Essentially all life depends upon the soil, and its important functional attribute, productivity for plants, is due more than anything else to the operation of biological forces, particularly vegetation. There can be no life without soil and no soil without life : they have evolved together.

All features of the natural landscape, conceived as the total environment for living organisms, are interdependent. There is a relationship between climate and vegetation, between parent rock and vegetation, between age and slope, and even between climate and slope. All express themselves in the soil, which is the final synthetic expression of the forces in the natural landscape together, and by which the nature of the landscape can be characterized better, more completely and more directly than by any other factor or combination of factors.

Every soil type, local or general, has its own elastic limit ; each offers certain possibilities, and each has rather definite limitations of production within the particular economic and social framework existing at any time. Man obtains from the soil, first of all, his food. Primitive man must adapt himself physically to the diet that nature furnishes or move to a more agreeable place.

With the advancement of knowledge and improvements of technique man is able to improve the products of the soil, according to his requirements and taste, through careful breeding and fertilization. Although several deficiencies such as those of calcium, phosphorus and nitrogen, may be corrected, by the modern scientist, many of the minerals and vitamins necessary to man occur in such small quantities in plants that their presence and effects still remain obscure. Each of the great soil groups is characterized by certain general levels of plant nutrients. The forested soils of Western Europe and Eastern United States for example, are commonly low in phosphorus, calcium, and the bases generally. In the great grassland areas of central North America and Eurasia these nutrients may be plentiful, but iodine may be deficient. Many soils in the humid tropics are especially deficient in phosphorus. Local soil types may have excesses or deficiencies of such elements as sodium, magnesium, selenium, chlorine, cobalt, nickel, boron, or copper responsible for significant influences upon food plants.

**Agricultural Techniques.** The needs of man extend far beyond what nature, unassisted, can furnish him. He must plough and sow—he must work with nature and conduct her producing forces through carefully organized channels. From the accumulation of experience and knowledge, man gradually learns to bend natural forces to his advantage and thus reduce the hazards of life and lessen his direct dependence upon the natural environment. Thus, it is through the use of techniques that civilized man produces his particular necessities.

Yet no matter how complicated become these techniques, social or individual, the fundamental fact of agriculture, the relationship between the plant and the soil in which it is grown, remains. The very responsiveness of soil to technique is one of its unique characteristics, individual and finite. Unconsciously man adjusts himself to these physical requirements, individually and collectively. His daily life, his work and his play, from the simple acts of life to the more complicated economic mechanisms he creates, are conditioned

by the necessities of his landscape. The agricultural techniques that man employs are basically designed to produce a relationship of soil to plant suitable to the aims of man.

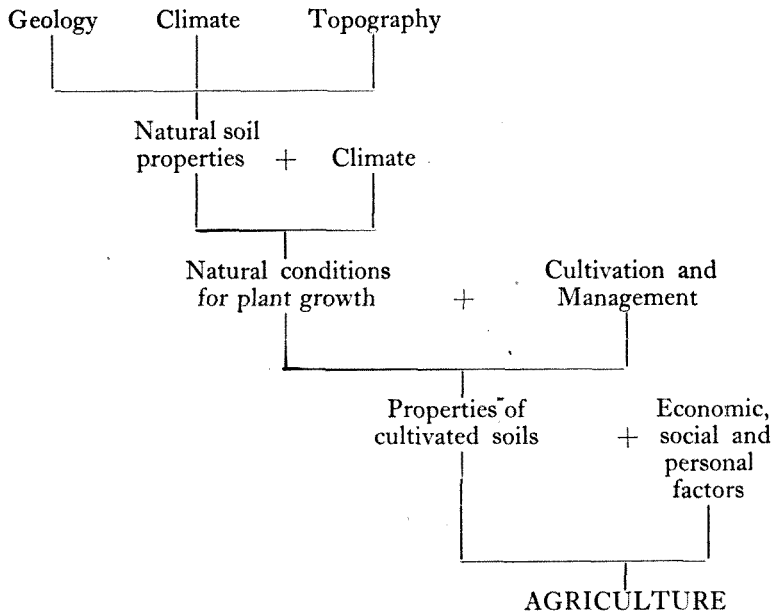
Theoretically, there are two general approaches to this adjustment : (1) Change the soil ; or (2) Choose plants to fit the soil. Usually man combines the two to some extent. While the proper selection of plants most nearly adapted to the natural soil is of the utmost importance, only rarely can crops be grown without tillage and other assistance from man. Further, the plants naturally adapted to the various soils vary greatly in their usefulness to mankind. Through the use of techniques many soils can be made productive of other than the native plants.

These agricultural techniques may be divided roughly into two classes : (1) those more or less simple methods carried out by the farmer and his family with relatively simple implements. For centuries these have been developing according to the conditions under which the farmers found themselves. (2) Those techniques more directly dependent upon the collective effort of the social group as a whole—the social techniques. Included in this group are those which may be largely physical, such as the development of electric power, and others that are largely institutional or legal. These are determined by the state of knowledge, basic interests, and cultural outlook of the group.

**Agriculture and Soil Productivity.** The earliest cultivations of soil were in arid and semi-arid regions, and it has been shown that in the westward migrations into Europe the first settlements were in forest-free regions, the loess areas, which in their general character resemble steppe. For primitive agriculture, the steppe or prairie offers much better prospect for successful crop production than the forest soils of humid regions. Under steppe, the climatic conditions, though drier than in humid regions, are more dependable. There is generally sufficient moisture after the winter for the establishment of crops, whilst the hot dry summer is favourable to ripening and harvest. Further, the moderate leaching tends to the conservation of plant nutrients and the inhibition of the deteriorative processes which operate in humid soils. The chief problem is water supply and yields are determined mainly by this factor. It is significant that the principal wheat areas are on the black earths and the chestnut earths.

In spite of the more intensive agriculture of the humid regions

of Western Europe, the cultivator is actually engaged in a perpetual struggle with the conditions which militate against arable culture. One of the principal differences between soils of the tshernosem group and soils of the podsolic group is in their structure. Whilst the calcium saturated soils of the former class naturally tend towards the desirable crumb structure and demand a minimum of cultivation, the podsolic soils tend to assume the single-grain structure. The cultivator is therefore always attempting to establish a structure which is purely artificial. The leaching consequent



on the high rainfall results in an impoverishment in mineral constituents, principally lime, which, if unchecked by applications of calcareous dressings, eventually results in deterioration, accompanied by loss of the desirable crumb structure. The actual labour of husbandry is increased by the fight against weeds, and the anxieties of harvest operations. It is perhaps no exaggeration to say that the efforts of the farmer in the humid regions are directed towards the production and maintenance of artificial tshernosems.

The agriculture of a particular locality is the reflection of a complex of factors, of which climate, soil, and situation are the most

important, since they impose certain limits on the choice of crops for cultivation. But economic, social, and even personal factors also intervene, with the result that the agriculture of a country only partially reflects the variations in soil and climate within its borders, and may undergo changes from generation to generation in response to causes other than those arising from fundamental natural factors. The inter-relationships of these factors may thus be represented schematically as in the chart on the opposite page.

A satisfactory apprehension of the nature of the contract between the soil and the living plant must be preceded by a thorough understanding of the composition of the soil. This relationship constitutes the chief human interest in the soil. Whatever be the nature of the contract between soil and plant, it is evident that a principal duty of the soil is to furnish the growing plant with an adequate and balanced supply of the nutrient elements.

The carbon, which forms about 55-60 per cent. of the dry organic matter, is obtained by the process of carbon assimilation or photosynthesis from the carbon dioxide which forms about 0.03 per cent. of the atmosphere. This change consists essentially in the formation of starch from carbon dioxide and water, probably through formaldehyde and dextrose as intermediate stages, with concomitant liberation of oxygen. The reaction or chain of reactions is endothermic and the source of energy is the sunlight. A further condition for the process is the presence of chlorophyll, the green colouring matter of plants. Except in so far as carbon dioxide is produced in the soil by the oxidation of organic matter, the soil cannot be considered as of direct importance in carbon assimilation. The hydrogen and oxygen of organic matter are obtained ultimately from the soil moisture.

The remaining elements of the dry matter of plants, namely, nitrogen, and the elements present in the ash, namely, sulphur, phosphorus, calcium, magnesium, potassium, iron, silicon, and all the other elements which, though not in all cases essential to growth and reproduction, normally occur in plants, are obtained from the soil.

Additions are constantly being made to the list of elements considered necessary for plant growth. Thus, during recent years, boron, copper, zinc, and iodine, have been shown to be essential, as we pointed out in previous chapters. They were overlooked by earlier workers on account of the minute quantities required relative to the other nutrient elements. The traces of impurities present

in the materials used for culture solutions were often actually sufficient to supply these elements. It is likely that the list of nutrient elements will be further enlarged. Progress is limited by the inadequacy of ordinary analytical methods. It is probable that the adoption of micro-chemical and spectrographic methods will enable considerable advances to be made in the survey of the essential elements for plant growth and their occurrence in soils. In the meantime, it is possible that some of the obscurer cases of infertility in soils may be due to unascertained deficiencies in trace elements.

It is generally supposed that the elements thus obtained, often termed plant nutrients, enter the plant root by absorption from the soil solution ; and much of the theory of plant nutrition has been built up on the basis of experiments in which plants are grown in so-called culture solutions. It is possible, however, that the mode of absorption by the plant may not be so simple as this theory implies. N. M. Comber has put forward the suggestion that the colloidal material of the soil and the colloidal material of the plant roots may form a single system within which translocation of material may take place.

There are, however, other factors involved in plant growth. Apart from the water required for the actual material of plants, water is required by the roots of plants to make good the constant losses by transpiration from the leaves. It has been found that, for every part by weight of dry matter formed, from 200 to 10,000 parts by weight of water are required. The supply of water to plants is intimately bound up with the supply of oxygen required for the respiration of the root system of plants. An excess of soil water, whilst not necessarily disadvantageous in itself, restricts the air supply to roots. On the other hand, an excess of air, not in itself harmful, implies a deficiency of moisture. Between the two extremes lies the optimum, which is often considered to be fulfilled by a 50 per cent. saturation of the pore-space of the soil and water. In most habitable lands fertility and infertility depend mainly on the moisture and air relationship of soils. The most frequent cause of infertility is deficiency or excess of moisture.

The next factor to be considered is negative, namely, the absence of injurious or toxic substances. The most obvious cases of inhibition of plant growth due to this group of factors are seen in soils in the vicinity of lead, copper, tin, or zinc mines, where the presence of

compounds of these metals partially or entirely excludes vegetation. The considerations advanced in discussing "trace" elements in nutrition are applicable to injurious elements. Cases of infertility may occur where the injury is due to small traces of elements whose presence in the soil has hitherto been unsuspected.

The tendency to degeneration of soils in humid temperate regions is always present, but the highly developed agriculture of countries such as England, Holland, and Belgium, is sufficient proof that the struggle against it is no impossible task and that, with cheap fertilizers and skilful tillage, crop yields can be obtained which would not be possible in drier regions.

Under the conditions of the humid tropics, the maintenance of an artificial system of land utilization is beset with even greater difficulties. The tendency to deterioration of virgin land brought into cultivation is far more rapid than in temperate climates. The high temperatures lead to a very rapid destruction of reserves of organic matter with consequent deterioration in physical condition, whilst the torrential tropical rains, acting on such soils, produce vigorous erosion. It is not surprising, therefore, that there are many instances of newly broken soils becoming completely derelict within a few years through injudicious management.

In many parts of the world, the most serious consequence of cultivation is erosion. We have already referred to the widespread erosion in the Eastern United States, which has taken place within comparatively recent times. Through uninstructed utilization of land in past generations, much irreparable damage has been done over large areas of the tropics and sub-tropics. It is important, therefore, that future agricultural operations should be conducted with the fullest possible precautions against further losses.

Loss of organic matter is not the invariable consequence of bringing land into cultivation. Where grass husbandry is practised, or where heavy dressings of organic manures are given, as in market gardens, the organic matter content of the soil may be maintained or even increased. In general, the loss of organic matter is least where livestock farming is practised, for it is then possible to return to the soil a considerable proportion of the crops raised and fed to stock, in the form of manure.

G. W. Robinson found a cultivated soil in Caernarvonshire in N. Wales, to contain 0.490 per cent. nitrogen, and to have an ignition loss of 16.6 per cent., whilst the adjoining waste, from which it had

been reclaimed, contained 1.106 per cent. nitrogen and gave 43.1 per cent. ignition loss.

The crops obtained immediately after bringing virgin land under cultivation are always bigger than succeeding crops. It is the common experience that yields fall off as the land is longer under cultivation. Under virgin conditions, the demands on plant nutrients are comparatively slight, for a large proportion of the nutrients extracted from the soil by plant roots is returned to the soil again in the form of plant residues. Under pioneer cultivation, the soil is cropped continuously and deterioration is inevitable. Firstly, there is a rapid exhaustion of plant nutrients as crop after crop is removed, and secondly, there is, in many cases, a physical deterioration in the soil consequent on loss of organic matter. This is manifested by a decreased water-holding capacity and an increased liability to erosion.

The deterioration consequent on pioneer cultivation of virgin land may be checked where live stock husbandry is practised, for it is then possible to return to the soil a considerable proportion of the nutrients extracted from it by crops. Organic matter may also be maintained by green manuring. The introduction of artificial fertilizers, whereby the plant nutrient status of the soil can be controlled, marks a further stage in land utilization. With the present abundance and cheapness of fertilizers, the serious problems of continuous agriculture are mainly physical in character. Indeed, in some systems of agriculture, crops are grown almost entirely on added fertilizers, and the role of the soil is mainly physical. This is the case over a large part of the cotton lands of the United States.

The utilization of land for irrigation brings its own set of problems. In many instances, the continued addition of irrigation water has led to a rise in the water-table, whereby injurious salts have been brought to the surface. In other cases the irrigation waters used contain excess of sodium over calcium salts, with the result that the irrigated soil is gradually changed from a calcium to a sodium soil with consequent deterioration and ultimate disaster to crops. Fortunately, the behaviour of saline and alkaline soils has been so thoroughly studied that the soil chemist can afford immediate help in proposing remedial measures for soils threatened by deterioration through alkalization. (*See Chapter 13.*)

**Significance of Soil Productivity.** Productivity can only be postulated in terms of particular crops. Thus, certain sandy soils are fertile for market garden crops, but unsatisfactory for grass. Soil

productivity might be defined in general terms as the ability of a given soil to grow satisfactorily some or all of those crops which are permitted by the regional climate.

**The Task of Applied Soil Chemistry with regard to Soil Productivity.** The principal task of applied soil chemistry is the discovery of limiting factors and the means of their improvement. We may review briefly the problems which the soil chemist is called upon to solve when he attempts to give assistance to practical agriculture.

(1) Firstly, he is called upon to show how soil productiveness measured in yield per acre or hectare can be most economically increased. To answer this question he must know the effect of cultivation and management, crop rotation, and manurial practice on plant growth under the particular conditions of climate and soil encountered in his district or country.

(2) Secondly, given the particular type of land utilization, he should be able to lay down the conditions under which yields may be maintained at an economic level and the soil guarded against deterioration and loss.

(3) Thirdly, he must be able to prescribe the measures to be taken, if economic conditions should demand a change in the system of land utilization.

It must be admitted that the present state of our knowledge falls far short of that necessary for the adequate solution of these problems—in so far as they apply to the actual growth of crops. Yet their solution is none the less urgent in view of present production levels. Plan and order are necessary alike for expansion and restriction.

There appear, however, to be two approaches to the solution of the problems of soil productivity and soil management. In one, knowledge is acquired by observing the effect on crop production of various methods of cultivation, management, cropping, and manuring. By isolating the variables and applying the latest statistical methods the results thus obtained can be given the highest significance. Yet the results of such experiments contribute little to increasing our knowledge of the master-problem of the contact between soil and plant.

**Soil-less Cultivation.** The subject of "Hydroponics or the Soil-less Culture of Vegetables" is one which over-publicity has led people to believe fantastic possibilities from the development of science. There is nothing new in it as a method of growing plants.

What is new lies in trying to see whether we can make a practical application of it to our commercial methods. Can we successfully grow plants of high quality and high food value without any soil? Is there any advantage in so doing? We want to outline the methods which have been tried and refer to some of the results which have been obtained; and, the possible future development.

Plants have been grown in nutrient solution under experimental conditions for nearly a century, and modern scientific agriculture has been greatly aided by information obtained through these studies. The keynote of plant growth is water. All life originated in water. All live protoplasm depends upon a high degree of hydration with water and the story of fertility in the soil and of growing plants without any soil is the story of giving the plants the water they need. If you give them the water they need, then the other sides of the story, the supply of nutrient and other conditions, can quite easily be attended to. But if fertility of the soil is regarded primarily as a problem of keeping a plant supplied with water, it will easily be seen how it links up with the story of cultivation of plants without soil.

What people try to achieve by soil-less cultivation is the control of the moisture conditions for the plant, and thus make sure that the plant always gets the water it requires at the time it requires it. Of almost equal importance, and bound up very closely indeed with the water supply, is the opposite factor of the air supply. All living things require oxygen, consequently, unless the roots of plants, which are very actively living things, obtain the oxygen they require they will not thrive. The whole of successful plant-growth is to supply at one and the same time sufficient water and sufficient air. That is the first basis of cultivation of the soil.

In soil-less cultivation methods the first problem is to ensure an adequate water supply and an adequate air supply, and complete control over the nutrient supply of the plant. It must be made quite clear that there is a vast difference between the nutrient supply of the plant and its food supply. Plants use the same foods as humans do. All protoplasm uses the same food, primarily, carbohydrates, proteins and fats. The only difference between plants and animals is that plants make their own foods; animals have to have their food made for them. Plants do not absorb food from the soil. The fallacy that they do so arises from our use of the words "feeding the plants," when we give nutrient to them. We do not supply foods to plants. A plant does not absorb food by its roots but it does absorb nutrients

which are just as vital to the plant as are the mineral salts we have to obtain from our foods. All living organisms require vitamins. But there is again the difference that the plants manufacture their own ; they do not absorb vitamins from outside ready-made. On the other hand, the majority of animal organisms have to have the vitamins elaborated or in a complex form from which they can themselves elaborate them.

**Methods of Soil-less Cultivation.** There are two basic methods that may be employed in achieving soil-less cultivation. (1) One is to grow the plant in the nutrient solution with its roots constantly immersed in the solution. (2) The second method is to grow the plant in some inert material which serves as support or anchorage for the roots, but otherwise plays little part, and from time to time to bathe the roots or supply nutrients to the roots in solution. There are various modifications of these two systems.

(1) The first method only requires brief mention. The method to which the term "hydroponics" was in the first place applied by Gericke in California and to which that word should be confined, if it is used at all, i.e. the method of growing plants with their roots immersed in liquid, and supporting the plants on a wire tray over shallow tanks of nutrient solution, was used first on a commercial scale in California.

(2) There are several methods of growing plants in some inert mineral aggregate, such as sand or gravel. Either of these two materials or almost any other inert material can be used. Perhaps the simplest method of all is to grow the plants in a clean washed sand which is flooded from time to time with the nutrient, or watered from overhead by means of perforated pipes, or simply by the water-can, with the nutrient solution. That method has the great advantage that the sand can be placed in any sort of container : wooden tanks, concrete or metal tanks, or even in pots or boxes on a small scale. It is a method used by scientific research workers on the nutrition of plants.

An interesting modification of sand-culture of plants has been tried on a commercial scale. The modification lies in growing plants in a mixture of sand and peat and supplying the chemicals in the solid form sprinkled on to the sand and subsequently watering them in, a method which is half-way between the ordinary soil cultivation and true-soil-less cultivation.

Another modification is known as the sub-irrigation system.

Briefly, the system is to grow the plants in gravel contained in concrete tanks some 6 in. to 8 in. deep. The nutrient solution is contained in separate storage tanks below the level of the concrete tanks, the gravel being flooded with the solution by means of an electrically-driven centrifugal pump. When large enough, the plants are transferred into the gravel and the watering or supplying with the nutrient takes place from time to time, whenever the plants require it, by flooding the gravel by means of the pump to within  $\frac{1}{2}$  in. to 1 in. of the top of the gravel and immediately allowing the nutrient solution to flow back again into the supply tank.

The basic principles of the system are that the nutrient supply and the water supply to the plant are kept reasonably constant, because the gravel is thoroughly flooded with the solution at regular intervals. The gravel holds sufficient moisture to carry the plant over until the next pumping, which may be only a few hours later. At the same time, the second great need of the plant for oxygen is achieved because as the nutrient solution which has flooded the gravel flows back again it obviously draws fresh air down into the interstices of the gravel, so that the roots are re-aerated and at the same time there is washing away of any accumulated carbon-dioxide or other toxic products which may have come from dead or decaying roots. That is the first and essential advantage of the sub-irrigation system over all the others.

The method of sub-irrigation has been extensively used in the utilization of sandy soils in Egypt. Excellent flower and citrus plantations have been established on sands in the Royal estates near Cairo through this method.

**The Nutrient Solution.** The essential elements, probably some fourteen or fifteen in number, though the list is being added to daily, can all be supplied readily from simple inorganic salts. It is a common practice to use as the source of nitrogen, nitrate of soda or sulphate of ammonia, preferably the former, as a source of phosphate, superphosphate of lime, and for potash, sulphate of potash. The fourth essential is magnesium in the form of magnesium sulphate. In addition, a regular supply of iron is necessary. Also certain of the minor nutrients, which may not be present in sufficient quantity as impurities in the major elements are best added in minute quantities in the form of boric acid, manganese sulphate and, possibly, one or two others, such as molybdenum. Chilean sodium nitrate is very useful in that respect as it contains—in addition to nitrogen—

about 30 minor elements which will otherwise be very difficult to add to the nutrient solution. The composition of the solution is certainly straightforward and presents no serious difficulty.

It is necessary to watch carefully that the total concentration of the nutrient solution is not allowed to become too high. Obviously one will not start with it too high. Unfortunately, plants do not take up the nutrients as a whole. The plant does not take up the sulphate and the potassium part of potassium sulphate at the same rate. The sulphate gets left behind in the solution and has to be balanced by something. It is balanced by hydrogen and therefore sulphuric acid appears in the solution ; this tends to make the solution much richer in sulphate and also considerably more acid. So that there are two difficulties : first, that the reaction of the solution is constantly changing, because of the plant's action on it, and the unequal absorption of salt ions and water ; secondly, that these unassimilated residues tend to accumulate in the solution and raise the total concentration. Since there is this unequal absorption by the plant in that it does not take up all the elements in the solution, evenly, it follows that a certain measure of chemical control of the solution is essential.

**The Possible Future of Soil-less Cultivation.** In California and certain places in the United States, extravagant claims were made for enormously increased yields. Many of these claims for high production are beyond the potential of any plant. Higher yields ought, however, to be obtained because control over the plant's nutritional supply should result in more uniform plants giving more uniform yields and, therefore, higher average yields.

Vegetables are not the only crops that can be grown by soil-less cultivation. Almost any plant can be grown by these methods. Any plant that can be grown in soil can be grown in gravel. But if we are going to adopt a system such as the sub-irrigation system, we have to face the fact that it does entail a considerable capital cost in outlay on the original plant. Therefore, clearly, only those crops which will give a high return for a relatively small area can be contemplated. These crops are almost inevitably glasshouse plants. Probably there is no future with these methods for large-scale production of outdoor crops. Obviously they cannot give a high enough yield per square yard to pay for the initial cost of installation of plant. Sir Albert Howard, however, holds the view that soil-less cultivation can never have a future because if plants are divorced from their

natural conditions in fertile soil, they cannot for that reason have a proper food value.

In the development of air transport, the line which has the best catering service at its various airports will attract—other things being equal—a larger number of passengers, and it is in the problems of catering at airports in desert and inaccessible areas that soil-less cultivation has an opportunity of being of great value.

## CHAPTER 26

### *The Literature of Soil Chemistry and its Use*

THIS chapter is an attempt to direct the student, although perhaps not to guide him, in finding his way about the literature of Soil Chemistry and to enable him to follow intelligently the future development of the subject.

The following are the main books and journals which deal wholly or partly with soil chemistry.

#### BOOKS

(1) *Soil Conditions and Plant Growth*. By Sir E. John Russell. Revised edition, 1949. This may fairly be described as a "reference library of the subject for the student and a comprehensive necessity for the specialist." It gives a full account, with abundant references, of the science of soil conditions.

(2) *Soils. Their Origin, Constitution and Classification*. By G. W. Robinson. Third edition, 1949. This is a modern account of Pedology dealing especially with genetic classification and profile studies. The first section of the book is occupied with the origin, constitution, and properties of soils, and the standpoint adopted is the exhibition of soils in their natural relationships. The next section is devoted to the description, with illustrative examples, of the chief soil groups of the world. This is followed by a discussion of the problem of classification, and an account, given with due reserve, of the geographical distribution of soils. In the remainder of the book the author dealt with soil surveys and soil analysis, and has concluded with a brief discussion of the inter-relationships of soils, plant growth, and agriculture.

(3) *The Principles of Soil Science*. By A. A. J. de Sigmond, 1938. Translated from the Hungarian by A. B. Yolland.

The English translation has been slightly abbreviated from the original but contains all the essential details of one of the most comprehensive systems of soil classification yet proposed. Prof. de Sigmond bases his system on the chemical properties of soils which, he shows, reflect very clearly the main genetic, morphological and biological characteristics. De Sigmond is the leading protagonist of chemical soil classification and his opinions command universal respect. The appearance of this lucid English exposition of his principal work is opportune at a time when chemistry has fallen rather into disfavour with soil taxonomists.

(4) *Soils and Men*. Yearbook of Agriculture, 1938. United States Department of Agriculture. Pp. 1232. Illustrated. Maps. For sale by the Superintendent of Documents, Washington, D.C.

A remarkably complete text-book of applied soil science. Contents : Part I—The Nation and the Soil. The problem defined, its causes and remedies : the soil and the law. Part II—The Farmer and the Soil. Tillage, soil fertility, farm management, fertilizers, erosion and its control, dry farming, irrigation, drainage, forest soils. Part III—Soil and Plant Relationships. Soils, plant and animal nutrition, minor elements. Part IV—Fundamentals of Soil Science. Soil and Society, physics, chemistry, and biology of soils, soil formation, soil classification, and mapping. Part V—Soils of the United States.

(5) *Humus*. By S. A. Waksman, 1937, is a comprehensive treatment of the study of humus.

(6) *The Study of the Soil in the Field*. By G. R. Clarke. Second Edition. Clarendon Press, Oxford, 1938.

This little book on soil surveying and mapping has deservedly reached a second and enlarged edition within a few years of publication. The amendments and additions incorporated in the second edition further increase the book's already recognized usefulness to the student of soil in the field.

The first chapter, which explains how to describe the site characteristics of a soil, includes a fuller account of G. Milne's recently introduced term "catena", used to describe recurrent soil characteristics due to land relief. The description of humus types is brought up to date with the inclusion of the more recent definitions of forest humus now grouped under "mull" and "mor". There is also an

account of the modern classification of peats and a description of Krasiuk's scheme for recording soil texture in the field.

An account of the author's system of texture classification, a modification of the Russian and American systems, adds considerably to the volume of the chapter devoted to soil-profile description. The section dealing with the drainage characteristics of the profile is extended to include an account of a system of soil classification based on drainage and vegetation. In the newer edition more attention is paid to the description and use of sampling instruments, and several different types of soil borers are described.

(7) *Colloids in Agriculture*. By C. E. Marshall, 1935—gives a simple general account of the properties of colloids, of soil colloids and of the colloids of plant and animal products.

(8) *The Diagnosis of Mineral Deficiencies in Plants*. By T. Wallace. H.M. Stationery Office, London, 1943.

This book has been written "primarily for the use of technical officers and advisers concerned with problems of crop production, and for progressive farmers, vegetable growers and fruit growers." It is written in simple non-technical language, and contains a considerable amount of practical information and facts that are quite as necessary for the research worker as for the advisory officer or farmer.

There are introductory chapters dealing with the essential facts of plant nutrition and the relation of soils thereto, and the various methods of determining mineral deficiencies—plant and soil analyses, injection and spraying, field trials, visual diagnosis—are enumerated and briefly described. Only the visual method is suitable for the non-technical observer, but if certain pitfalls are avoided it can be as reliable as any. The main part of the text consists of descriptions of the visual symptoms of deficiencies of both major and minor elements in all the common agricultural and fruit crops.

Special mention should be made of the method, devised by the author, of diagnosis by means of indicator plants. These are plants which display quite specific symptoms for certain deficiencies: they are usually particularly susceptible to those deficiencies and show them in accentuated form, e.g. beets and mangolds display boron-deficiency symptoms, potatoes and oats specific manganese-deficiency symptoms. A scheme is given whereby by means of a series of fertilizer experiments on selected indicator plants the main soil

deficiencies that are likely to arise on a newly cultivated area can be detected in one cropping season.

The book can be strongly recommended to all interested in plant nutrition, whether from a physiological or pedological point of view.

(9) *Soilless Growth of Plants*. By C. Ellis and W. S. Miller. Wiley (N.Y.), Chapman and Hall (London), 1938. Contents : Chemistry of Plant life. Growing in Mineral Aggregates. Sand-Culture Method. Sub-Irrigation Method. Growing in Water. Water-Culture System. Nutrient Solutions. Household Plant Culture. Growing Flowers for the Family. Growing Vegetables for the Family. Commercial aspects. Special Chemicals. Plant Hormones. Doubling Chromosomes in Plants. Effects of Miscellaneous Chemicals on Plants. Common Detriments. Nutrient Formulae. Index.

(10) *Soil Analysis*. A Handbook of Physical and Chemical Methods. By C. H. Wright. Second Edition. London. Murby, 1939.

Contents: Introduction. Part I—Physical Methods. Preparation of the Sample. Moisture Loss on Ignition. Keen-Raczkowski Measurements. Moisture Equivalent. Moisture Content at different Humidities. Freezing Point. Heat of Wetting. Moisture Content at the Point of Stickiness. Soil Shrinkage. Density and Pore Space. Mechanical Analysis. Hydrogen Ion concentration. Part II—General Chemical Methods. Calcium. Magnesium. Potassium. Sodium. Phosphoric Acid. Indicators for Volumetric Analysis. Standard Solutions for Volumetric Analysis. Part III—Special Chemical Methods. Nitrogen. Ammonia. Nitrites. Nitrates. Carbon Dioxide. Carbon. Organic Matter. Mineral Constituents. Clay Fraction. Inorganic Soil Colloids. Hydrochloric Acid Extracts. Available Phosphoric Acid and Potash. Water Extracts. Soil Solutions. Base Exchange Appendixes—International Atomic Weights. Gravimetric Factors and their Logarithms. Volumetric Factors. Index of Authors. Index of Subjects.

(11) *Soil and Plant Analysis*. By C. S. Piper, D.Sc. Pp. 368. Adelaide, 1947. Contents : Part I—Methods for the Examination of Soils. The Collection and Preparation of Soil Samples. Hydrogen Ion Concentration, Conductivity and Water Soluble Salts. Mechanical Analysis. Single Value Soil Constants. Soil Colour. Standard

Solutions and Indicators. Calcium Carbonate. The Analysis of the Hydrochloric Acid Extract. Exchangeable Ions and Exchange Capacity. Nitrogen. Nitrates, Nitrites, and Ammonia. Organic Matter. Free Ferric Oxide. The Separation and Analysis of the Clay Fraction. Part II—Methods for the Determination of the Inorganic Constituents of Plants. The Collection and preparation of Plant Samples. Methods for the Ashing of Plant Material. The Determination of the More Common Inorganic Constituents. The Determination of the Trace Elements.

(12) *Official and Tentative Methods of Analysis of the Association of Official Agricultural Chemists*. Seventh Edition, 1950. Published by the Association of Official Agricultural Chemists of America.

The book is a record of the standard chemical and physical methods adopted by the Association. It is a most valuable contribution to Agriculture. The methods outlined in that book are unique in several respects. They are the outgrowth of critical continual collaborative trial or test participated in by a large number of workers and undertaken in order to establish the accuracy of analytical results. The first part of the book is devoted to the methods of analysis of soils and fertilizers.

## JOURNALS AND REPORTS

(1) *Internationale Mitteilungen fur Bodenkunde*. Proceedings of the International Society of Soil Science. The "Internationale Mitteilungen" was initiated mainly by the European soil chemists in 1911. In 1924, after the publication of its 14th volume, it was transformed into the "Proceedings of the International Society of Soil Science," which society was formally founded in that year. These Proceedings are published quarterly in English, French, German, Italian and Spanish at the International Institute for Agriculture, Rome, and constitute a part of the "International Review of the Science and Practice of Agriculture."

In addition to this quarterly publication, the Proceedings of Conferences of the International Society and its constituent "Commissions" are published separately.

These publications are definitely scientific and are admittedly of chief importance to the specialist.

The International Society of Soil Science (General Secretary,

Dr. D. J. Hissink, Groningen) meets quinquennially in full congress. In addition there are meetings of the six commissions, into which the society is organized. There are numerous publications in connexion with the congresses and the commission meetings.

(2) *The Journal of Agricultural Science*. The Journal of Agricultural Science was launched in 1905 by British agricultural scientists. Its inception was largely an effort to rescue a considerable amount of technical and scientific matter from the comparative oblivion of college bulletins, leaving these bulletins indispensable to any soil library.

(3) *Soil Science*. This journal was initiated in 1916 by Rutgers College in the United States, with Dr. Jacob G. Lipman as editor-in-chief. It is published monthly and has now (1950) reached its 69th volume. It contains nearly all the important American soil papers, and is a necessity in any Soil Reference Library.

(4) *Journal of the Science of Food and Agriculture*. A new journal (1950), from the Society of Chemical Industry, of wide scope and of high technical standard.

(5) *Miscellaneous*. There are some noteworthy soil papers, although mainly of more interest to the specialist, in *The Proceedings of the Royal Society*. The journals of almost any of the general scientific societies—e.g. *The Journal of the Society of Chemical Industry*—occasionally publish soil papers. The Faraday Society has twice held a symposium on soil subjects—*Physico-chemical Soil Problems* in 1921, and *Base Exchange Phenomena* in 1925. The papers are published in the Society's *Transactions*. There is also a considerable amount of soil matter distributed through the many bulletins of agricultural colleges and research stations. Much of this is often very inaccessible, but its amount is rapidly diminishing under the influence of the established journals.

## ABSTRACTS AND RÉSUMÉS

(1) *Annual Reports of the Progress of Applied Chemistry*. This yearly report has one section devoted to agricultural chemistry in its broadest sense and should be perused by all who wish to follow the advance of the subject.

(2) *Publications of the Imperial Bureau of Soil Science*. (Harpندن, England). (a) *Soils and Fertilisers*. A bi-monthly publication of abstracts covering a wide field of literature. The abstracts are arranged in suitable sections and each is indexed on the decimal system. (b) *Bibliography of Soil Science*. This bibliography is accumulated from "Soils and Fertilisers," is published in four-yearly numbers and affords a very complete index, again by the decimal system, of the literature on soil science.

(3) *Chemical Abstracts*. This is a publication of the American Chemical Society which was commenced in 1907 and is published twice a month. Section 15 is devoted to abstracts of papers relating to soils and fertilizers.

(4) *British Abstracts*. (B) Applied Chemistry, Section III, i, Agriculture. This section of the abstracts covers a wide range of agricultural matter and includes all the principal literature of soil science and related subjects. It is advantageous to have abstracts of agricultural research and those concerned with the utilization of many agricultural products (foods, sugar, fermentation products) in a concise unit published separately from the general mass of abstracts.

Another section of the abstracts (C), also published separately, covers analytical methods. One sub-section (iii) of this includes all abstracts of papers dealing with soils, etc.

(5) *Die Jahresberichte für Agricultur Chemie* is a German production of very long standing devoted to Abstracts. It has periodic collective indexes.

There is naturally much repetition of labour in abstracting, many papers being abstracted in all the abstracting publications. This, however, is not wholly unfortunate, for the abstracts vary considerably and it is often possible to get a much better conception of the paper from several abstracts together than from any one of them alone.

The books and journals named are those commonly used in the author's experience, and the student who is familiar with them will inevitably find reference—particularly in the abstracts—to others.

## THE USE OF THE LITERATURE

There are two general reasons for the serious student of scientific agriculture necessarily having a general familiarity with the literature

of the science of the soil. One is that he may have occasion to consider in some detail the work done on a particular problem, the other is that he must be able to keep in general touch with the whole development of the subject. No "rules" can be attempted for the achievement of these two ends, but the following general remarks may be useful.

*Surveying the Literature of a Specific Problem.* The agriculturist who needs to ascertain whether any investigations have been carried out on a particular subject, and if so, with what results, will in the first instance naturally turn to such books on the soil as are available and will particularly search the bibliography and references in "Soil Conditions and Plant Growth."

Many institutions concerned with the subject will have a card index that may be useful, but the subject of soil science is so diverse that references in the most complete card index may not be grouped together in the manner required, and in using a card index one has to consider every possible heading under which references to the particular problem might be found.

The indexes of one, or perhaps several, of these abstracting publications will be consulted, usually starting with the most recent issue and working backwards as far as is thought necessary. Care has to be taken to think of every possible word under which the subject might be indexed, for it is easily possible to miss the reference one wants because the indexer has put it under a heading which does not occur to the reader. So far as is possible the original papers abstracted should be seen. It is not always necessary to read them in every detail, as many of them have a few pages of summary and conclusions at the end.

When searching for papers dealing with a particular problem, one frequently finds one paper which gives a résumé of work on that problem up to the date of its publication and the student may therefore often make use of the labours of other people.

The particular procedure adopted, however, depends on the problem and the extent to which one wishes to be acquainted with its details. Experience of using the literature is the most effective way in which one can decide how to proceed in respect of a particular problem, and these remarks are made in the hope of stimulating the student to acquire some such experience.

The Annual Reports of the Society of Chemical Industry will be useful in this connection and the agriculturist who wishes to keep

his knowledge of the soil abreast of the times should take what opportunities are possible of looking through the later issues and editions of some of the journals and books with which he became acquainted during the period of systematic study.

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