

maintained for efficient production and that there are few conflicts between those systems of management that give the greatest economic return and those that insure the continued improvement and conservation of the soils.

We have learned that many kinds of soil that gave low yields with the practices of only a generation ago can be used efficiently now. If those soils are protected under grass or trees, the United States can increase its acres of cropland very greatly if the need arises. Thus we have many choices in soil use and no real need to use unresponsive or high-risk soils for cultivated crops.

What we seek is not some kind of mythical natural balance between farmers and the soils they cultivate, but a cultural balance in which we use with understanding and precision all the tools of modern science, engineering, and economics.

## The Basis of Fertility

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The old and new meet in soil management. From ancient days man has plowed, drained, terraced, and irrigated land. He has manured his crops and has used rotations, either blindly or by plan.

Early man was limited by not knowing how things happened. When a background of knowledge had developed to the point where the question of *how?* could be approached, further progress was possible. That progress was late, even in the period of recorded history—between 1800 and 1850.

Humphry Davy, an English chemist and a professor of the Royal Institution in London, made one of the first steps toward explaining the value of manure and ashes. He wrote in 1813:

“If land be unproductive, and a system of ameliorating it is to be attempted, the sure method of obtaining the object is to determine the cause of its sterility, which must necessarily depend upon some defect in the constitution of the soil, which may be easily discovered by chemical analysis.”

Twenty-seven years later, in 1840, Davy's ideas were still being debated and had not been put to wide use on farms. At that time the German, Justus von Liebig, the foremost organic chemist of his day, was turning his attention to the problems of soil fertility. In his book, *Organic Chemistry in its Applications to Agriculture and Physiology*, he pointed out that the chemical elements in plants must have come from the soil and air. If fertility is to be maintained, the loss from the soil must be replaced.

Even before Liebig had so emphatically pointed out the essential basis of fertility, others were conducting tests.

Prominent among them was John Bennet Lawes, who was devoting his estate at Rothamsted, north of London, to the purpose. In 1840 Lawes was trying out the effectiveness of crushed bones as a source of phosphate for plants. He found the bones to be quite ineffective, contrary to Liebig's teachings. Lawes reasoned that a more soluble type of phosphate compound was needed. To prepare such a material, he and his associate, J. H. Gilbert, in 1842 treated bones with sulfuric acid. The resulting fertilizer came to be known as superphosphate and is the basis of much of our present fertilizer industry.

The concern of Liebig, Lawes, Gilbert, and other agricultural chemists between 1840 and 1860 centered on the elements required in large amounts for plant growth. These include nitrogen, potassium, and calcium as well as phosphorus. The success of super-

phosphate (P) as a fertilizer quickly led to the wide use of soluble potassium (K) salts and compounds of nitrogen (N) in complete fertilizers. Thus, N-P-K as components of a complete fertilizer, or rather  $N-P_2O_5-K_2O$ , as we know them on our fertilizer tags, came into being.

The principles involved in nitrogen supply to plants and in the production of nitrogenous fertilizers have developed since 1850. Liebig thought that plants derived their nitrogen from ammonia in the air. The French agricultural chemist and farmer, J. B. Boussingault, however, in 1838 on his estate at Bechelbronn in Alsace showed that legumes can obtain nitrogen from the air only when the soil or medium in which they are growing has not been heated. Boussingault argued that the free nitrogen of the air is changed into compounds suitable for plant growth by something that is alive in the soil. Heat killed the living organisms. The time, 1838, however, was too long before the development of bacteriology as a science to allow the organisms to be found.

Fifty years after Boussingault's experiments, a Dutch scientist, M. W. Beijerinck, isolated bacteria from nodules on legume roots. He showed that the bacteria, which came to be known as *Rhizobia*, or root living, had to be present for nitrogen to be taken up by the legume. It was the rhizobia that were killed by Boussingault's heating of the soil. But the 50 years between Boussingault and Beijerinck had seen the development of bacteriology by the German physician, Robert Koch, and by one of the greatest benefactors of mankind, Louis Pasteur.

This was discovery. It served to explain the importance of legumes in land use, but it did not give the principles for changing the nitrogen of the air into soluble compounds.

The way in which nitrogen can be caused to react with other elements is basic to its fixation from the air. The principles of this fixation process are needed, both for an understanding of

the part played by the legume bacteria as well as for the creation of a fertilizer industry. Both depend on catalysts, which are materials for speeding up reactions that otherwise are too slow to be effective.

Metallic iron is the most effective catalyst for promoting the combination of nitrogen and hydrogen to form ammonia,  $NH_3$ . This catalyst was developed by the German chemist, Fritz Haber, in the early years of the First World War.

Haber knew from the principles of chemistry that the catalyst could only increase the rate of combination of the nitrogen and hydrogen without changing the degree of their combination—that is, the equilibrium between nitrogen, hydrogen, and ammonia. To obtain the greatest degree of combination required pressures of many hundreds of atmospheres and temperatures of about 800° F. But even under those conditions, the combination did not take place unless the catalyst was present and iron was the best catalyst.

Haber's successful synthesis of ammonia answered the most serious problem of soil management and of world food production, a supply of nitrogenous fertilizers. More than 3 million tons of ammonia are now produced yearly in this way in the United States from the elemental nitrogen of the air and hydrogen, obtained chiefly from natural gas or petroleum refining.

The catalysts that promote nitrogen fixation by rhizobia growing on legume roots are still unknown. The German bacteriologist, H. Bortels, in 1930 showed, however, that free-living forms of nitrogen-fixing bacteria will grow in the absence of nitrogen compounds only if they have a supply of molybdenum. Bortels reasoned that some molybdenum compound must be the catalyst in bacteria for nitrogen fixation. On the basis of this idea, he showed in 1937 that nitrogen fixation by clover, beans, and peas was greatly enhanced by an adequate supply of molybdenum.

The practical application of Bortels'

findings first came in Australia, where large areas were known to be unsuited for pastures containing clover. The agronomist, A. J. Anderson, showed in 1942 that this condition could be corrected by use of a few pounds an acre of molybdenum compounds mixed with superphosphate, for the soils were deficient also in phosphate.

Another discovery about the association of nitrogen-fixing bacteria and legumes was made by a Japanese scientist, H. Kubo, in 1939. He learned that the nodules containing the bacteria are effective only when a red pigment is present. He demonstrated that this pigment is a hemoglobin much like that of blood, which has never been observed under other conditions in plants. Herein is a suggestion to explain the uniqueness of legumes among plants for nitrogen fixation, but much more must be found to explain the process.

The importance of a rather rare element such as molybdenum as essential for establishing legumes introduces the minor nutrient elements. A group of these elements, which are discussed in detail in the chapters that follow, are known to be essential for plant growth.

The first to be recognized was iron, the absence of which leads to a general yellowing, or chlorosis, of leaves. A French scientist, A. Gris, in 1844 described how chlorosis of some plants can be corrected by sprays of iron salts. Progress, however, was slow, and it was not until after 1900 that the importance of other minor-nutrient elements such as boron, copper, manganese, and zinc was appreciated.

The principle of essentiality of these elements has been stated by D. I. Arnon, of the University of California, in this form:

"An element is not considered essential unless a deficiency of it makes it impossible for the plant to complete . . . its life cycle; such deficiency is specific to the element in question and can be prevented or corrected only by supplying this element; and the element is directly involved in the

nutrition of the plant quite apart from possible effects in correcting some unfavorable microbial or chemical condition of the soil or other culture medium."

Most minor—or "trace"—nutrients act as required parts of enzyme systems, the catalysts of living things, that speed up the reaction necessary for growth, although many of these enzymes are still to be discovered.

Thus molybdenum acts in nitrogen fixation as a part of some enzyme system; it also is required for the reduction of nitrates in plants, the enzyme required being nitrate reductase. The element is also required in animals for the oxidation of xanthine, a material similar to uric acid, which must be oxidized before it can be eliminated adequately.

A PRINCIPLE intimately involved in fertility, but with broader implications as well with regard to physical features of soils, is that of base or cation exchange. Today this is often a first factor to consider in management, as it involves liming of acid soils and amelioration of alkali soils.

The principle is that soils act to hold base elements such as calcium, sodium, potassium, and magnesium and the acid element hydrogen. Generally, one element can only be replaced by another. Thus, as calcium is removed from soil by plant growth, or by leaching with water, its place might be taken by hydrogen until the soil is too acidic for use. This is the tendency in most soils of the Eastern and Southern States.

The principle of base exchange was discovered just a little over a century ago by the Englishman, J. T. Way, an associate of Lawes at Rothamsted.

Way was concerned with the possible loss of water-soluble fertilizers from soil by leaching. He established instead that the soluble material was held and displaced an equal amount of material present in the soil. This was a fundamental principle. It foreshadowed by three decades the development of a

part of modern chemistry, namely, the law of mass action, later (1867) stated by the Scandinavian scientists, C. M. Guldberg and Peter Waage.

The law of mass action formulated the idea that in a chemical reaction such as  $A + B \rightleftharpoons C + D$ , in general, or  $Na^+ + H \text{ soil} \rightleftharpoons H^+ + Na \text{ soil}$ , in particular, an equilibrium is attained. If, then, A is increased, the reaction will be driven toward the right; if D, toward the left. Thus, acid,  $H^+$ , increase displaces sodium, Na, so that it can be washed from soils. This is the basis for the use of sulfur as an acid-forming element in the recovery of alkali soils.

The principle of base exchange and that of mass action expressed in the reaction  $Na^+ + H \text{ soil} \rightleftharpoons H^+ + Na \text{ soil}$  is in a very general form, in that inquiry is not made into the nature of H soil and Na soil.

This serves some of the requirements of management, but it does not explain, for instance, why Na soils often have very poor drainage and why one soil differs markedly from another when both have high sodium contents. The ends of management both for use of many soils under irrigation in the Western States or for recovery of land from the sea, as in the Netherlands, require a more detailed knowledge of Na soil.

Way, in the period near 1850, established that the base exchange was due chiefly to the very finely divided materials in the soil. Prominent among these materials were the clays, and Way made synthetic materials by precipitating aluminum and silicon compounds that somewhat resembled the clays and possessed base-exchange properties. But these synthetic materials, which have long been exceedingly important for softening water, differed markedly from clays in many of their properties, such as the capacity to remain suspended in water without change. An understanding of base exchange, then, became largely an effort to understand the nature of clays. This search was successful after 1925.

We can separate soils into fractions of various particle sizes by shaking them through sieves and by suspending them in water. The coarse fractions are sands. The intermediate ones down to the limits of microscopic magnification are silt. Those below these limits are the clays, which settle very slowly in water.

If a soil after separation into fractions is reconstituted with omission of the clay, its cohesive properties will be greatly diminished, particularly if the soil is a loam or heavier in clay content. The clay, then, apparently is the fraction involved not only in base exchange but also in interaction with water in soil. In management, as an example, the clay interaction with water is determinative for many properties, such as those underlying the tendency of soil to erode and its features of internal drainage.

The basic principles about clays are to be found on an atomic scale. You might think it strange that this is the case for such gross features of a field as its lime requirement, its tendency to erode, the draft requirement for plowing, or the required spacing of drains. These properties of the whole field, though, are only reflections of the most minute parts. While the four features are quite different in external appearance, they might depend on the same (or on only a few) minute features.

KNOWLEDGE ABOUT CLAYS on the atomic scale advanced only after a long period of development in the basic physics of atomic structure. In principle, to work with phenomena on a particular scale, the measuring instruments must have features on that scale. Thus, for measuring a mile to the nearest foot, a measuring tape need only be divided into feet, which would make it unsuited for measurement of thickness for a plastic film.

The desired basic information about clays was the arrangement of the atoms. The measuring method that proved useful in finding the arrange-

ment was the diffraction of X-rays.

X-rays are like visible light in that they can be resolved into different wavelengths by diffraction and refraction. In visible white light, the resolution into the different component wavelengths or colors by refraction is shown in a rainbow. This resolution can also be done with an ordinary window screen and a light by diffraction, as can be seen by looking at a distant light through the screen. The degree to which the various colors are separated depends on the fineness of the screen—the smaller the separation of the wires, the greater is the color separation. The diffraction then can be used to measure the wire separation in the screen.

X-rays have wavelengths, equivalent to color in visible light, of about the same value as the separation of atoms in clays. The atoms in the clays, as in all crystals, irrespective of size, are arranged in an orderly and repeated manner much like the men in an army passing in review. This arrangement corresponds to the wires of the screen for visible light. Accordingly, the diffraction of the X-rays by the atomic arrangement in the clays can serve to measure the arrangement.

The kinds of atoms present in the clays are chiefly silicon, aluminum, and oxygen, with small amounts of the basic elements such as calcium, magnesium, sodium, and potassium, and the acid element hydrogen. They are the ones taking part in base exchange. This knowledge of composition came from the analysis by chemists of many pure clays collected from mineral deposits by geologists and mineralogists.

The diffraction of X-rays by a clay shows that the silicon atoms, which are relatively small, are each surrounded at the corners of a tetrahedron by larger oxygen atoms and that each oxygen atom is between two silicon atoms, which thus serve to link tetrahedrons together. The aluminum atoms, which are similar in size to silicon, are substituted, in part, in place of the silicon atoms. The tetrahedrons upon

linking are formed into sheets, and two of these atomic sheets are joined by aluminum atoms between them.

This arrangement of the atoms in the clays has three features, which are the basic ones underlying many properties of soils. These features are: The atoms are arranged in sheets; the surfaces of the sheets are largely the surfaces of oxygen atoms; and the attraction between atoms in the sheets depends on the relative number of oxygen, silicon, and aluminum atoms.

As a result of the atomic arrangement in sheets, the clays can be split between the sheets and thus reduced to particles that are exceedingly thin. The clays therefore are finely divided; that is one of the necessary features for formation of a mud.

OXYGEN ATOMS on the surface result in attraction of water molecule through binding with the hydrogen atoms of the water. In other words, the sheets have a high tendency to be wetted with water. In one type of clay, as a matter of fact, water molecules on the sheet surfaces separate the sheets and cause the clays to swell. It is for this reason that many of the alkali soils have such poor drainage. It is the basic reason for the cracking of many soils during prolonged droughts.

If the attraction of the atoms is not balanced on the scale of atomic dimensions, other atoms must be present for the balance. These atoms can only be present on the surfaces of the sheets. On the surfaces they can readily be separated in the water layers that are also there. Accordingly, they are the atoms that can be exchanged with others—the atoms of base exchange—the atoms involved in the acid reactions of soils and the liming requirements.

As knowledge of clays developed, it was found that there are several ways of making the atomic arrangements in sheets and that clays with different arrangements differ considerably in such properties as the amount of their base exchange and their tendencies to swell in water.

A first question about most soils is, "What is the clay type?"

This question is accompanied by, "What is the soil texture; how much clay is present?" Finally, "What is the base-exchange capacity?"

A guiding method for learning more about clays in soils was to work on pure clays and from their properties to assess their degree of contribution to the general properties of the soil. Other soil components also affect these properties, and the part played by organic matter or humus can be great. Can the principles basic to the action of organic matter also serve as a guide through some of the complexities of soil?

Until the time of Liebig, the idea was held that humus was directly used by plants and as such contributed to soil fertility. Liebig showed that plant growth instead depends upon inorganic compounds. Organic matter is useful for fertility only as it is broken down with release of the constituent nitrogen and phosphorus into inorganic forms. Even today, though, some nonagricultural persons maintain that humus has direct attributes in fertility.

With the advance near the end of the last century in knowledge of bacteriology and the requirements of micro-organisms for growth, it became evident that humus was, in part, a product of the action of micro-organisms and, in part, their sustaining food. The release of the nutrient elements required the destruction by micro-organisms of the organic matter from past crops or that of the native soil. From this point of view alone, the best practice would utilize the organic matter as rapidly as possible.

The organic matter has other properties. One is base exchange, or the capacity to hold nutrient elements, such as potassium, calcium, and magnesium, in saltlike combination much as do clays. Destruction of organic matter naturally reduces this exchange capacity of the soil.

The desirable effects of organic matter on the structure and, through these effects, on the physical properties

of soil are of greatest importance. This is the discovery of no particular person but it is readily observed by all who are familiar with soils. It has to do with mellowness and friability, with the maintenance of a good tilth, and the preservation of a loose and uncompacted soil.

The question of principle would be to establish how organic matter contributes to desirable structure in soil.

The answer has not been found even by repeated inquiries into the nature of organic matter. Rather, it seems that something still is to be established about the interaction between organic matter and surfaces of clay minerals.

The most progress in this regard was the finding that some of the polymeric compounds related to the materials of plastics but containing more acid groups when added to clays or to soils have the desired action on structure. The principle, as vaguely formed, involves, in part, the presence of a number of acidic organic groups held together in one molecule that is resistant to attack by micro-organisms.

These acidic groups interact with the surfaces of the clay minerals. The natural materials possessing these properties, in part, are gums formed by bacteria. They are not very stable against further attack by bacteria, however, and have to be constantly renewed by supplying fresh organic matter for the bacteria to consume.

Fertility, the properties of clay, and the functioning of organic matter are examples of factors in soils for which basic principles have been sought.

Each principle is treated in chapters that follow. Other principles also are expressed, particularly with regard to the behavior of water in soils for which a basic understanding is well developed.

In the end, the search for principle is the only way by which we can gain information from one soil that is useful for farming another soil. Information about properties of the individual soils become an orderly and consistent part of knowledge about all soils.