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THE STRUCTURE AND PHYSICAL PROPERTIES OF SOILS.[1]

THERE is no more important economic problem to-day than the production of food and textile fibre to support the life of a rapidly increasing population and to supply their rapidly increasing wants in this age of advancing civilization. Agriculture is the basis of all manufactures, trades, and commerce, and the soil is the basis of all agriculture. This was not generally recognized until Liebig's brilliant generalization of the mineral theory of plant growth, and there was in consequence no material advance in agricultural methods or practices until his time. Since then this mineral theory has been the subject of a vast amount of the most patient research, carried on in the field, laboratory, and plant house. At first it was only considered necessary to determine the chemical composition of a soil and the composition of a given crop to indicate whether the soil had all the elements of plant food in the relative amount contained in the plant, to show whether the soil was well adapted to the crop, or how it could be made so by the addition of chemical substances. Then it was found that all soils have sufficient plant food for ages to come, and that continued cropping during the lifetime of a man would not reduce this amount materially. Then it was claimed, and is still held by many, that only a very small part of the plant food in the soil is in a condition to be readily available to plants, and if this available food is not used up it quickly reverts to a rocky and insoluble form. Then it was endeavored, by the use of solvents of various strengths, to determine how much of this plant food is at any time available to plants; and failing in this, the work has been pushed blindly forward with plat experiments, trying all kinds of mixtures of all kinds of fertilizers, on all kinds of soils, indiscriminately, as one might go into a drug store in the dark and blindly try all the drugs to cure dyspepsia, for it is dyspepsia that affects the plant more often than any thing else,—an inability to appropriate and assimilate the food within reach. We are spending vast sums of money for commercial fertilizers, which are used indiscriminately on all classes of soil, whether they be light and sandy, or stiff with clay.

The physical character of the soil has been considered, in all or nearly all the investigations I have ever seen, a vague, complex, but, on the whole, a relatively unimportant factor. The soil is considered a unit. Soils differ physically, just as men differ physically. There is a type of soil suited to grass, another to wheat, others to the different grades of tobacco, and still others to trucks and vegetables. The whole appearance and aspect of the soils differ to the eye and touch.

It is a notorious fact that changing seasons of wet or dry, or hot or cold, have far more effect on the crops than any combination of manures. This in itself is a significant fact.

In ten years a soil may be so worn out as to become a barren waste. This is not from any loss of plant food, for the amount so removed from the soil is relatively so small that it cannot be detected with any certainty. But the fact confronts us, that the wheat and corn lands of the great North-west are deteriorating, and the wheat and tobacco lands of our own State are deteriorating, both as to quality and quantity of product.

I come now to the main point of this paper, that the exhaustion of soils is physical rather than chemical; that vegetation, under given climatic conditions, is dependent upon the circulation or movement of water in the soil, and that it is possible to change the physical conditions of the soil so as to control this water circulation, and so control the growth and development of the plant. Nay, further, that the chief benefit derived from the use of commercial fertilizers and manures is their physical effect on the soil, which modifies the relation of the soil to water, rather than, as heretofore supposed, to the actual amount of food they supply the plant. The soil is to be considered as a vast irrigating pump which provides standing room for the plant and supplies it constantly with nutritive fluids. If too much water is supplied the plant is inclined to develop leaf in large excess; if too little water is supplied the growth is stunted, but it puts on relatively more fruit. It is a mean between them that is desired for all plants, but a different mean for each class of plants.

The soil is composed of minute fragments of rocks and minerals, with varying quantities of organic matter. Even the poorest and most barren soils are shown by chemical analysis to have sufficient plant food for countless generations of plant life, while in ten years or less a soil may be "worn out," and made for a time a barren waste.

However compact and continuous and close textured a soil or sub-soil looks, there is still about fifty per cent by volume of empty space between the solid particles. That is, a cubic foot of soil will hold half a cubic foot of water, if all the space is filled. Clay soils have more empty space than sandy soils. We have found on the average about forty-five per cent by volume of empty space in sandy soils and fifty-five per cent in clay lands. The amount of empty space in the soil may readily be calculated by dividing the weight of soil by the specific gravity, which gives the actual volume of the soil grains, and subtracting this from the total volume occu-

[1] Abstract of a paper read by Professor Milton Whitney of the Maryland Agricultural Experiment Station before the University Scientific Association, March 25, 1891.

pied by the soil. The light sandy sands, therefore, are light only in texture, for a cubic foot of sand weighs about one hundred and ten pounds, while an equal volume of clay weighs seventy-five pounds.

The water of the soil has to move in this empty space, and the relative rate of movement will depend upon how many particles there are in the soil, for this will determine the number and size of the spaces between the particles in which the water will have to move.

The soil particles vary in size from about 2 millimetres in diameter to about .0001 of a millimetre, which is near the limit of microscopic vision. The coarser particles are called sand, while the very finest particles are known as "clay." We cannot emphasize this point too strongly, that clay differs from sand only in the size of the grains. The particles of clay are hard and compact as sand, are composed largely of quartz, and they have themselves none of the inherent stickiness associated with clay in mass.

The plasticity of moist clay and the hardness of dry clay in mass, as distinguished from the looseness and incoherency of sand, is due to the fact that the clay has a vastly greater number of particles in a unit mass than sand has, and as each grain touches the surface of six or eight adjacent grains, there are many more points of contact for surface attraction to act and bind the mass of clay together.

The approximate number and size of the particles may be found or calculated from the mechanical analysis of a soil. The mechanical analysis consists in separating the particles into eight or ten or more grades whose diameters range between rather narrow limits by sifting and subsidence in water.

The mechanical analysis in its simplest form, as devised by Nöbel and adopted some years ago by the Society of Agricultural Chemists of Germany, consists in boiling the soil for some time in water, to disintegrate any lumps, and placing it in the first of a series of conical-shaped vessels having a capacity respectively of 1, 8, 27, 64. A stream of water is let in which carries the finer particles over into the next succeeding larger vessel, where, the motion of the water being slower, grains of somewhat smaller size may settle, and so on. Many small grains are, however, carried down with the large ones, and Hilgard has improved on this by having a paddle revolving at a high speeed in a porcelain cup, which keeps the soil thoroughly agitated. From here the mixture rises into a wide tube sufficiently high so that large grains thrown up by the current of the paddle will not go over. When the water comes over clear the receiving vessel is changed, and the velocity of the water is increased so as to carry over grains of a larger size. Johnson and Osborn have simplified this in the following method. The soil is gently rubbed up in a mortar with a rubber pestle with repeated quantities of water, until the water, after standing a moment over the soil in the mortar, is perfectly clear and all grains smaller than .05 of a millimetre have been removed, as shown by microscopic measurements. The coarser grains are then sifted in a series of sieves.

The turbid liquid is allowed to stand until all particles, larger than a certain size, have settled, as shown by microscopic measurements on a drop of the liquid removed with a rod or tube. The turbid liquid is poured off into another beaker to settle, and the contents of the first beaker is stirred up with a fresh quantity of water, and the settling continued until all particles, smaller than a certain size, are removed, and so on for the several grades. The separations are finally dried and weighed.

The following table gives the mechanical analysis of two markedly different types of soil: —

Diameter in Millimetres.		Truck Soil.	Limestone Sub-soil.	Approximate Number of particles in 1 gram.	
				Truck Soil.	Limestone Subsoil.
2 to 1	Fine Gravel.	1.41	0.00	3	0
1 " .5	Coarse Sand.	8.19	0.00	142	0
.5 " .25	Medium Sand.	43.78	0.18	6,094	26
.25 " .1	Fine Sand.	24.04	0.26	32,930	371
.1 " .05	Very fine Sand.	5.81	2.39	101,000	43,350
.05 " .01	Silt.	8 61	27.60	2,341,000	7,825,000
.01 " .005	Fine Silt.	1.98	10.74	34,430,000	195,000,000
.005 " 0	Clay.	4.48	53.02	1,952,000,000	24,450,000,000
		98.23	94.19	1,988,911,169	24,652,868,747

From the results of the mechanical analysis, the approximate number of particles in the soil can be calculated from this formula: —

$$\frac{a}{\frac{\pi (d)^3 2.65}{6}} \div \text{total weight of soil.}$$

Where a is the weight of each group of particles, d the mean diameter of the particle in the groups, and 2.65 taken as the specific gravity of the soil.

From this and the weight of a unit volume of soil, the number of particles on a unit area of surface can be calculated.

$$\left(\sqrt[3]{\text{No. particles in 1 cc.}}\right)^{\frac{2}{3}}$$

There will evidently be one space or opening into the soil for every surface grain. If the grains have a symmetrical arrangement the mean size of these spaces can be calculated from the formula: —

$$r = \sqrt{\frac{V}{\pi N L}}$$

Where r is the radius of the space, V the total volume of all the space, N the number of spaces on a unit area, and L the depth of soil.

The circulation of water through the soil will depend upon the size of these spaces, and not in any simple ratio either, but according to the fourth power of the radius multiplied by the number of spaces. You will bear in mind we are not trying to establish absolute but relative values.

Here are ten tubes, each with a radius of three units, and here is one single tube with a radius of ten units, having the same capacity and area of cross section of the ten tubes. If they were exceedingly small capillary tubes water would flow through the single large tube about twelve times faster than through the ten tubes. So it is in the soil. If we assume that there is the same amount of empty space in a clay soil as in a sandy soil, there are at least ten times the number of spaces in the clay soil for the water to move through, and the movement is very much slower than in a sandy soil. Clay has no inherent property of absorbing and holding moisture not possessed by sand, as popularly supposed, the difference being due entirely to the number of particles per unit mass.

I want now to show you that the size of these spaces upon which the circulation of water depends may be varied at will by the ordinary commercial fertilizers used by farmers. And first let me show you the very simple but curious (for hitherto unexplained) phenomena of flocculation.

Here is some muddy water in this beaker. The particles of clay are so extremely small, and have so much surface in proportion to their weight, that the ordinary convection currents in the liquid are sufficient to keep them in suspension for an indefinite time. A trace of salt, kainit, or acid will cause the clay to come together in light, loose flocks, like curdled milk, and these flocks will quickly settle and leave the water above perfectly clear. If only a trace of these substances has been added, a few drops of ammonia will neutralize this effect, and break up the flocks and push the clay particles without the range of their mutual attraction, so that the liquid will not clear for days or weeks or years.

When this is watched under the microscope, the particles in the turbid liquid when ammonia is present — if they are very small and freely suspended in the liquid — do not ordinarily come very close together, or if they do they are shoved aside by an elastic cushion. When the least excess of acid, salt, or lime is added, however, they not only come close together but segregate in large flocks, which float around as though held by a rigid hand. If too much acid has not been added, the further addition of ammonia will push the particles apart again, but this cannot be kept up indefinitely, for the accumulation of the salt formed causes a permanent flocculation, which we have not yet been able to overcome.

As I have said, the reason for this has not yet been satisfactory explained, although it has formed the substance of several memoirs to the National Academy of Sciences and of a large bulletin of the United States Geological Survey. It is a phenomenon of great economic importance, as it accounts for the formation of flats and shoals at the mouth of rivers where they empty their muddy water into the salt waters of the ocean, for the curious periodic shoaling and deepening of the channel at the mouth of the Mississippi River with low and high water, and for the peculiar clearness of limestone water. It is a phenomenon also of the utmost importance to agriculture.

I am glad to say that Dr. Kimball has taken an interest in it, and has given valuable aid and suggestions, and I believe we shall be able to work it out before long, as we already have a very plausible and tentative explanation awaiting experimental verification.

I will try to show you that similar forces may act in the soil, and produce very material and important modifications in the arrangement of the soil grains — changing in a very remarkable degree the relation of the soil to the circulation of water.

Here are three argand lamp chimneys eight inches long and two inches in diameter, the upper two inches of the tube being graduated on the side. Equal weights of the same soil occupies six inches in depth of each tube. The soil is the characteristic truck land of Anne Arundel County, — light, loose, and loamy; almost too light for wheat or grass, for water circulates too freely in it for these crops. An inch in depth of water passed through these saturated soils in just about the same time (twenty-five minutes): a few drops of a solution of kainit was added to the water in this second tube, and a few drops of ammonia to the water in this third one. The effect of the kainit, as in the muddy liquid, is to pull the fine particles of clay much closer to the grains of sand and to make the soil more loamy and looser in texture. The large spaces have become larger, and the small spaces smaller, and the effect of this, as you saw with the tubes, is to very materially increase the rate with which water circulates in the soil.

Now I do not pretend to say that even under the intense condition of my experiment this change is instantaneous, for it is not. While the acid or salt, or kainit or lime, makes it possible for the soil particles to come closer together, the motive power which actually brings them together is probably the changing temperature and changing moisture content, so that in practice the change in the physical structure of the soils will probably be very gradual, and be noticeable only after several years of continuous application.

Sir John Lawes has observed that the continued use of nitrate of soda has made his soil more loamy and porous. It is a matter of common experience that such changes occur in stiff clay land from the continued use of acid phosphates and lime, but no special significance has ever been attached to it, as it has been considered incidental to other benefits (hitherto unexplained, be it understood) derived from the application.

The effect of ammonia on the soil is even more remarkable, as it is so instantaneous, and the effect even in this short time is so marked. The ammonia loosens the hold of the clay particles on the grains of sand, and the currents of water in the narrow spaces seemingly are sufficient to detach them, as the liquid, before clear, is now muddy. The further movements can be watched under a microscope focused against the side of the tube. The clay flocculates immediately, probably from the effect of the salts in the soil, and these loose flocks, floating around, catch against the projecting sides of the grains of sand, and the spaces gradually fill up with this light, loose material.

The clay is more evenly distributed throughout the soil, and the circulation of water is very much retarded. While before the ammonia was put in, the inch of water passed through the soil in about twenty-five minutes, it will take it now at least six or eight hours.

From our own work it is probable that the organic matter of stable manure and the alkaline carbonate of wood ashes would have much this same effect, and I believe this is the reason the agricultural value of these substances on certain soils has always been out of all proportion to the amount of plant food they contain.

This interpretation of the results of the mechanical analysis of soils gives a very clear explanation of the marked adaptability of certain plants for certain characters of soils under the same climatic conditions. Truck, wheat, grass, and the different grades of tobacco all succeed best on soils which differ essentially in their physical properties. Not only so, but it is quite possible to calculate the relative rate with which water will circulate through these different types, and we have, therefore, a means of classifying soils by referring them to these types; and when the observed rate of circulation differs from the rate calculated from the mechanical analysis, as it does in "worn out" lands, we have the still more important information of the changes which have occurred in the structure of the soil, and we have seen that this may be varied at will by the ordinary fertilizing materials. I am satisfied that it is through some such careful study of the soil further advance in agriculture will be made and the most intelligent use of manures and fertilizers be secured.