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Reactions of Superphosphate in the Soil

by Olle Franck.

The original commercial phosphatic fertiliser was bone meal. This phosphorus compound is practically insoluble in pure water. When therefore, such a fertiliser is spread on the field, the phosphorus cannot be washed down and distributed by the rainfall through the soil layer in which occurs the main part of the plant root which takes in the nutritive salts. In any event, it does not get down to the root layer soon enough. In the case of agricultural crops the root layer which takes in the nutritive salts is usually two to eight inches below the surface of the soil. The grasses and other crops which are regularly cultivated have a root layer of considerable size. It is therefore necessary, when a fertiliser, not soluble in water, is employed, to work it in with the cultivator or plough.

In 1840 Liebig proposed treating bone meal and raw phosphate with sulphuric acid for the purpose of obtaining a water-soluble phosphate. Through the employment of a fertiliser containing water-soluble phosphoric acid, it was thought that phosphorus, in a form which could easily be taken in by the crop, could be distributed by means of the water in the soil layer in which the roots are present. Through this expedient the nutriment was supposed to be made easily available to the crop.

As early as 1850 it had been found that phosphorus combines in the soil into many difficult soluble compounds so that it is necessary considerably to diminish its reactivity with soil water. The fact that the transformations of water-soluble phosphates, such as occur in the soil, are as rapid as we now know them to be does not, however, seem to have become fully clear at that time. In any event, what was questioned at the time was the practical behaviour of the fertiliser and not the full consequences thereof. With regard to the distribution of the phosphate in the soil in a suitable manner, it became the practice to depend on the water-solubility of the phosphoric acid in superphosphate, and to neglect more and more the working of the phosphatic fertiliser down into the root layer.

A light harrowing, however, brings the fertiliser only down to a depth of one half to one or two inches, and hence does not get it into the real root zone. Even by repeatedly working the soil with a deeply penetrating cultivator it is not possible to work the fertiliser into the soil to a depth of more than two or three inches. A large part of the fertiliser, therefore, remains in the topmost layer, even after a deep harrowing, where there is practically no root growth and which is, furthermore, bone dry during a large part of the growing season, unless the fertiliser has been washed down into the soil by rain.

At the Bureau of Soil Research of the Department of Agriculture (Sweden) extensive research and experiments relating to phosphate problems have been conducted during the past 15 years. One of the reasons which induced us to devote special attention to phosphate problems was the contradictory and illogical results which have so often been obtained, not only in repeated fertilising experiments in the field, but also in comparing the findings of the field experiments with certain biological and chemical processes in agriculture which the Department desired to study.

Thus, in carrying out field experiments in acid loam in accordance with the conventional methods - that is, employing, as the varying fertiliser, a comparatively small amount of superphosphate which was not harrowed in very far - it was usually found that the phosphate fertiliser had no effect, despite the fact that the content of plant-soluble phosphoric acid in the soil was so low, according to chemical analysis, that there seemed every likelihood that an increase in the phosphate factor would bring about a considerable improvement in the final crop. In box experiments, carried out according to Mitscherlich's method, however, we obtained excellent results with phosphate fertilisers. No phosphorus could have been taken from the sub-soil since this was even poorer in phosphate than the humus. In the box experiments, tests were arranged also so that the phosphoric acid would be available both locally - through intermixture in all of the soil in which the roots grow - and physiologically - through very large amounts of phosphate, that is, in the proportion of about 1,760 pounds to 2,640 pounds of superphosphate per acre, with plenty of water.

Whether or not the phosphate factor is satisfactory can certainly be determined by box experiments. And in this instance the box experiments do show that the phosphate condition of the soil is unsatisfactory. Hence, the box experiments and the chemical analysis of the soil are in agreement but not the field experiments. The first problem to be solved, therefore, is why plants in the field experiments are not able to make use of the available phosphoric acid.

The following is a description of some of the work carried out by the Bureau of Soil Research (Sweden) for the purpose of clearing up this problem, together with the results obtained.

In order to determine how the soluble phosphoric acid in superphosphate behaves in the soil, the following series of experiments was arranged: Six different types of soil were studied. Portions of two pounds of each type of soil were weighed out, and mixed with increasing amounts of superphosphate. The soil was then put in a glass cylinder and saturated with water poured in from the top. After the cylinder had been dried in the air, the phosphoric acid was partly water- and partly lactate-soluble.* It was found that the behaviour of this lactate-soluble phosphoric acid gives a good idea of the behaviour of plant-soluble phosphoric acid.

According to these tests, phosphoric acid is not retained in the water-soluble form in any large amounts, that is 15 to 20 per cent, except in sandy ground, rich in lime (pH 7.4). In neutral loam, only 7 to 9 per cent remain in the water-soluble form. Still less remains in acid soil, and least of all in very acid clay, in which only about 1 per cent remains in the water-soluble form. In the lactate-soluble form, 63 per cent remain in the lime-rich sand, in the loam 27 to 43 per cent, in the acid soil about 30 per cent, and in the very acid clay only about 16 per cent.

It should also be noted that the larger the amounts of phosphate employed, the larger proportionately are the percentages remaining in the soluble form. This is particularly true of the nearly neutral loam, where the soil seems to be very close to the saturation point of phosphate. The prepared lime-rich sands reach the saturation point with the least addition of superphosphate.

Some research workers, investigating the water-solubility of phosphoric acid, when applied on fields, have found that practically all the phosphoric acid in finely pulverised superphosphate was converted into a form where solubility is difficult, within a short time after coming in contact with moist soil. After drying, the material is usually firmly fixed, and this fixation is still further increased if the soil is periodically moistened and dried.

* Lactate-soluble according to the method of the Swedish scientist Egnér.

The difficulty which the phosphate experiences in being transported by the soil water must be compensated by placing it in the soil at the required depth. And the very extensive studies on cross sections of soils which the Department of Agriculture has made since 1931 show that this does, in fact, usually apply to all the natural soils, excepting sandy soils which are wholly free of loam, and to gravelly sand.

Thus the content of readily soluble phosphoric acids in soils, which are not regularly worked with the plough, was very high in the surface zone (0 to 2 inches), and fell off rapidly with deeper penetration. In fields, regularly cultivated, the ploughed layer was considerably richer in phosphate than the subsoil, and the dividing line between the two soils was clearly noticeable. Due to the fact that the fertiliser is not naturally carried down through the soil mass, the first requirement is to place it in such a way that it is locally available to the plants, that is, in the root zones. In a spring sowing experiment in a soil whose phosphate condition was unsatisfactory, 380 pounds of superphosphate were applied, a part harrowed in, and the rest ploughed in. Ploughing gave a yield of about 242 pounds more per acre than harrowing in. In another extensive experimental series, deeper and more thorough harrowing in of the superphosphate on soils which are extremely poor in phosphorus, gave average increases of about 38 pounds per acre.

It therefore follows that some kind of mechanical work is required in order to distribute the phosphorus in the soil. The growth process itself, however, serves to "pump" phosphorus from the deep layers of the soil to the surface layer. That is, the plant itself absorbs phosphorus through its roots and transports it to its part above the ground. Leaves fallen from trees and shrubs, dead vegetation, the excreta of animals, grazing in meadows and hayfields, return phosphorus to the surface, whence it is carried back into the deeper layers much more slowly than it was brought up. Thus the surface is kept very rich in phosphorus. This can be seen in cross sections of soils. For example, a cross section from a meadow in Central Sweden showed the following : 0 to 2 inches below the surface, more than 20 units of lactate; 4 to 6 inches below the surface, about 2 units of lactate; 6 to 8 inches below the surface, about 1 unit of lactate; 8 to 16 inches below the surface, about 0.5 unit of lactate.

When a field, which used to be cultivated, is turned into a pasture the difference in the phosphate content between the ploughed layer and the subsoil disappears. That is, the phosphorus diminishes at the bottom of the ploughed layer (through phosphorus being taken in by the roots) and increases right on the surface (through the animal excreta).

It is out of the soil water that the plant takes in through its roots its nutritive phosphate salts. The phosphorous content in the soil water of any soil is very low, regardless of the degree of fertility. That is, a quart of soil liquid usually contains less than twenty-two millionths of a pound of phosphorus. This means that in an acre of humus layer there is no more phosphorus than is contained in 9 to 45 pounds of 20% superphosphate. For example, it can be said, that, depending on the kind, size and condition of the crop, the amount of phosphorus used up per year per acre corresponds to between 132 and 440 pounds of 20% superphosphate. The low content of phosphate in the soil water does not, however, have much bearing on the problem under consideration, because any crop can easily take in phosphates from such diluted solutions as are here concerned. From the point of view of plant nourishment, however, it is of the greatest importance that the phosphorus in the soil water should be replaced as fast as it is used up by the plants. Certain solid particles of earth, which are to be regarded as fertiliser fragments, are suppliers of phosphorus. If the phosphorus is supplied to the soil water too slowly or in insufficient amounts, the plants suffer from phosphorus hunger, and the harvested crop is deficient both in yield and in quality. In other words, the phosphate condition of the field is unsatisfactory. The unsatisfactory phosphate condition may be due either to an excessively slow speed of supply, or to the fact that the phosphate reserves are running low, or to both of these causes.

Some of the metals, particularly aluminium and iron, are able, since they are present in the ground water in the ionised form, to exert an adverse influence on plant growth. This damage may be due either to a direct poisoning effect or to a lessened availability of the phosphate, caused by its combining with a metal to form an insoluble compound. Thus aluminium seems to be a specific root poison which prevents the root tissues from functioning normally. This metal is able to precipitate phosphate not only out of the ground water but even out of the very root tissues. This is why plants in very acid soils frequently show a deficiency in phosphate which manifests itself in broken leaves, or a strong reddish-violet colouring at the base of the stems, etc.

Various types of plants react very differently to an excess of aluminium or iron. Thus barley is much more sensitive than oats. Oats can more readily assimilate phosphoric acid at lower pH values, that is, when aluminium and iron are present in the ionised form.

The transformation of the metals, just mentioned, into the ionised form occurs, however, at different degrees of acidity (pH value) depending on the fundamental chemical composition of the soil. According to Mattson's researches, as published in a series of articles in "Soil Science", and according to the Annual Reports of the University of Agriculture (Upsala), the colloidal content of the soil is determined by the ionisation of the basic or acid constituents which are present in excess in the soil. When the quotient between the basic and the acid content is comparatively low, ionisation can take place only at a comparatively low pH-value. If, however, this quotient is high, then ionisation can take place at a comparatively high pH-value.

The cultivated fields of any farm, particularly the loamy ones, are characterised by a comparatively high quotient between the basic and the acid content. Hence, in such cases, a comparatively high pH-value is needed if the aluminium and iron are to be prevented from becoming ionised. However, a low pH-value is very common, with the unfortunate result that the phosphate condition is unfavourable.

According to recent findings, "the phosphate condition is improved" either by adding phosphate, silicic acid and humus, thus lowering the quotient, or by increasing the pH value through liming. However, the best results are probably obtained by employment of all the expedients already mentioned.

The excess of phosphorus in a form which can be readily taken in by the plants can be furnished by applying superphosphate in sufficient amounts. The soil is then, as the layman would say, "saturated" with regard to phosphoric acid. This, however, frequently requires such large amounts that it is not economically feasible to carry it out; that is, if it is a question of thus saturating the whole humus layer.

But is it really necessary to do this? It is known that a plant can "assign" certain roots to take in phosphate and other roots to take in the rest of the needed plant foods it requires. It would, therefore, seem that it is only necessary to saturate the soil to a suitable degree in those parts where the plant satisfies its requirement of phosphate, that is, in the root zone. Investigations on the growth of plant roots carried out by the Bureau of Soil Research do, in fact, indicate that such a solution to the problem is possible.

In order to study how the root system of a plant develops when superphosphate is present in different layers of the soil, a series of experiments were started in the greenhouse on March 24th, 1937, moved out into the field at the end of April, and terminated on June 1st and 2nd, 1937. The planting containers employed were wooden boxes, 12 inches high, 6 inches wide and 26 inches long. One of the long sides could easily be unscrewed in the longitudinal direction of the box; and two inches back from the removable long side a windowpane was inserted. In order to provide thorough ventilation, as well as access to water from below, a large number of holes were bored through the bottom. Water was provided from below by placing the box for a certain length of time in a shallow zinc tub where the water was one or two inches deep. In order to prevent the topmost soil layer from drying out, the soil was covered with a thin layer of coarse quartz gravel.

The moisture of the soil, when it was put into the boxes, was satisfactory for germination. Three and six weeks after sowing, it was watered by sprinkling, each time with an amount of water corresponding to 1 inch of rainfall. The watering from below- by placing the box in the zinc tub for three days - was undertaken whenever there was any tendency to droop. One-half of each box was sown with oats and the other half with barley. The experiment was terminated when the grain was about to go into spikes. The window pane was taken out, and the loose soil particles were carefully washed with water to expose the root system.

Two different types of soil were employed in the experiment; one a humus-bearing silty loam (pH value 5.1, lactate index 1.7) and the other a sandy soil, poor in humus, (pH value 5.4; lactate index 0.8). The findings were fundamentally the same for both types of soil. The growth was very uniform and satisfactory. Very soon there could be observed definite differences between the different fertilising treatment in the boxes. The unfertilised ones, and the surface-dressed ones, were soon behind the others. In the case of oats, full stemming was observed, in the deeply fertilised box, several days later than in the barley. During the same time, the unfertilised oats had developed only two blades, and the surface fertilised oats had developed only three blades with the beginning of stemming. The plants were thinned out on the same day from 15 to 6 of each kind of grain. In thinning out the oats, care was taken to observe any differences in root development due to differences in the fertilising procedures. The distance between the seed and the base of the stem was comparatively great in all of the specimens. In none of the unfertilised specimens was there observed any beginning of crown roots, while such a development was observed in the case of the deeply fertilised specimens. In the surface fertilised specimens there were several instances of well-developed crown roots, despite the fact that the development above the ground had not proceeded nearly so far as in the deeply fertilised specimens. In the barley no such differences could be observed. In both the oats and the barley the seed roots were much further developed in the deeply fertilised than in the unfertilised specimens. From these observations it might be assumed that it is not necessary to apply a phosphate fertiliser as far down in the soil for oats as for barley. It must not be lost sight of, however, that in these experiments the soil was kept continuously moist throughout, right up to the surface. Such a condition rarely prevails in the field. Instead, the surface layer in the field is usually more or less dried out during the growing season. Under these conditions the crown roots develop right above the seed.

When the experiments were concluded, both the oats and the barley were much further developed in the deeply fertilised than in the surface fertilised boxes. The unfertilised specimens were far behind the others, and this is only natural, since the phosphate condition of both of the soils employed was originally very poor. Both the unfertilised box and the box with the fertiliser distributed throughout the whole soil mass showed a network of roots very uniformly distributed throughout the whole soil mass. In the box in which the fertiliser was applied in the surface layer the branching of the roots was very considerable in the part below the surface layer, but where the roots penetrated further down there was almost no branching. Such a root system must be very ineffectual and very sensitive to drought. A surface application of a phosphatic fertiliser would, therefore, probably diminish rather than increase the final crop, particularly if the soil is very poor in phosphorus.

Where the fertiliser was disposed in two different layers (2 to 3 and 6 to 12 inches deep) there was a richly branching root system throught both of those layers, while in the intermediate un - fertilised layer the root branching was very insignificant.

In the box with the granulated superphosphate, compact accumulations of fine roots developed, squeezed together in bundles having a cross section of approximately one inch. If all of the soil was carefully removed, the root system looked like a birch tree which had shed all of its leaves and was full of so-called witches brooms. Inside of each such root bundle there was found a superphosphate particle which had not undergone any change whatever. The roots which had penetrated down into the soil and had come close to such a particle had evidently benefited from the good phosphate conditions in their immediate neighbourhood, and had put out a compact network of rootlets in order to take in the phosphoric acid which was easily accessible at this spot. The larger the superphosphate particle was the larger was the root bundle. It required a considerable amount of strength to tear such a root bundle apart. In this way the superphosphate particle was well protected against external influences. The superphosphate particle, therefore, remains uninjured when ploughing the ground as long as such a root bundle is intact.

As the root bundle decays, the accessibility of the phosphoric acid to the plant is increased to the utmost through the humus thus formed. Treatment of such areas with granulated phosphate for further crops will, for this reason, give particularly good results.

The phosphorus content was, therefore, considerably higher in the superphosphate fertilised layers. Where granulated superphosphate was employed, the average lactate value between the root bundles was 1.7, while the soil closest to the root bundles showed a lactate value as high as 14.

During the last 8 years we have conducted several hundred field tests with granulated superphosphate. The following table shows the result of a series made in Central and Southern Sweden on mineral soils with insufficient phosphorus content.

The crops were spring-sown cereals, in most cases mixed food or oats.

IE.5%.

Superphosphate in lbs per acre.	Experimental year Harvest in lbs per acre.						Average of 5 years experiments. Harvest in lbs per acre.
	1939	1940	1941	1942	1943		
No superphosphate, total yield	1898	1944	1584	2415	2420		2052
Additional yield with 88 lbs P_2O_5 as pulverised super. Broadcast.	+200	+112	+22	+164	+125		+130
as granulated super. broadcast	+266	+113	+88	+215	+340		+194
as granulated super. drill-sown.	+307	+255	+223	+326	+393		+301

Analysis of the results of various tests shows that granulated superphosphate has had a greater fertilising effect than ordinary superphosphate and that sowing in rows is better than broadcast.

There is no difference in principal between different years, despite the fact that the years 1940 and especially 1941 were extremely dry. On the other hand, the average effect of the superphosphate varied in different years. It was far less in the dry years than in those years when the rainfall was sufficient.

In dry years sowing of superphosphate in rows seems to be the only method that may give an economically good result.

Superphosphate is more suitable in granulated form. The finely divided superphosphate reacts much more quickly and intensively with the soil than the granulated superphosphate, thereby losing more quickly than the granulated form its ability to supply phosphoric acid to the plants. The large particles are able to saturate soil zones in such a way as to enable the roots easily to take in the phosphoric acid. The phosphoric acid which has been taken in can be replaced from the supply which has not yet completely reacted with the soil, that is, from the superphosphate particles themselves. The granulated superphosphate is a more stable phosphate and provides a more constant supply of phosphoric acid in the soil.

When the superphosphate is employed in the granulated instead of in the finely pulverised form, only part and not the whole of the soil is fertilised; that is, the part in which the plants have most of their roots which take in the nourishment. Of course, if a sufficient amount of phosphatic fertiliser is applied over a number of years in succession, then the final result is the same whether the superphosphate is applied in the granulated or in the finely divided form. In both cases the soil is finally saturated with phosphorus throughout its mass to such an extent that it is in the best condition from the point of view of plant nourishment. In applying it in the granulated form, a larger part of its phosphorus content will be available in a shorter time. This is very important, for most farmers do not have a very large amount of working capital. Many farmers would, therefore, find it economically impossible to supply all at one time the large amounts of superphosphate which would be required to put their whole soil mass into the best phosphate condition. At the same time, it might even result in harm and in losses of phosphoric acid to supply very large amounts all at one time to the plants. The granulated superphosphate, therefore, has a considerable advantage from the technical point of view. It is drier, does not rot the bags, and is not so likely to cake. The granulated form is also easier to apply, whether by hand or by machine.

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