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SELECTED ARTICLE

Soil Physics: Theory and Practice* (*Abstracted*)

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I. SOIL PHYSICS : ITS SCOPE IN AGRICULTURE

Agricultural science as we understand it today is a young growth. It is only in the past 25 years or so, that any considerable number of trained and competent scientists has been engaged in agricultural research, and with rare exceptions the agricultural laboratories have not celebrated a Golden Jubilee. The soil physicist was a relatively late arrival; there was no physicist on the Rothamsted staff until 1913.

The primary contribution of physics to agricultural science is obviously in the study of the soil, its physical properties, the laws governing the retention, movement and loss of water, and the bearing of these laws on plant growth. The practical applications of this knowledge largely concern the operations and their effect on soil moisture and on plant growth. Those are the main subjects embraced in soil physics : theory and practice.

Soil is, from the physical view point, a mixture of particles of all shapes and sizes ranging from sand grains and rock fragments a millimetre or so in diameter down to minute particles of clay or clay—like minerals. Every one knows the difference between a clay soil—a heavy soil as the gardener or farmer calls it—and a light or sandy soil : the latter has more coarse and fewer fine particles than the former. The Agricultural scientist requires a more exact and more objective specification than the term 'heavy' and 'light' and this has been met by the method known as the mechanical analysis in which the particles are sorted out into a number of groups of decreasing size.

In all methods of mechanical analysis the soil is mixed with water and treated to disperse any clusters or aggregates into their individual particles. The coarser particles are then separated under water by sieves of suitable mesh, while the small ones are graded by using the fact that the smaller the particle the more slowly it sinks in still water.

The table below gives the group names, the range of settling velocities and the equivalent radii of the particles, calculated from Stokes' Law, assuming that every soil particle is a perfect sphere. The equivalent radius is a convenient fiction which provides a more concrete picture of particle sizes than does the velocity of fall in water.

Name of group	*Range of radii mm.*	*Upper velocity of group—cm. sec.*	*Log. v*
Coarse sand	10—0·1	350	2·54
Fine sand	0·1—0·01	3·5	0·54
Silt	0·01—0·001	0·035	$\bar{2}$·54
Clay	Less than 0·001	0·00035	$\bar{4}$·54

The characteristic property of coarse and fine sand fractions is their inertness. Soils containing high proportion of them hold little water and are of low inherent fertility. Nevertheless they are an essential constituent of soil. They keep it open and thus improve the natural drainage, aeration and ease of cultivation.

The silt particles pack more closely together than any other soil constituent. Soils containing much silt—15-20%. are difficult to work and drain. Liming has

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* Cantor lectures delivered on 19th and 26th January and 2nd February 1942.

little effect on silty soils as, unlike clay, silt does not possess marked colloidal properties.

Clay is the most distinctive of all soil constituents. It is the weathered and chemically reactive portion of the soil, while others are inert. It displays marked colloidal properties. Its most striking property is the power to form crumbs or aggregates, consisting of many individual particles bonded together. Clay soils are retentive of water and drain only slowly. They warm up less rapidly and cool more slowly than sandy soils. They offer high resistance to cultivation implements. When wet, clay soils tend to become sticky and shrink on drying.

Much work has been done on the properties of the soil in bulk. The goal has always been what may be called a 'single value' measurement; some experimental procedure in which an outstanding physical property, or group of properties, would be specified by one numerical value, and thus serve as a simple means of grading or classifying soils. Such single values can clearly have only a general significance.

One difficulty that besets the prediction of soil behaviour in the field from the results of single value determinations is that many of these necessitate the soil being in a finely divided condition. The natural crumbs have to be broken down mechanically and the main characteristic of the field soil is, therefore destroyed. The crumbs are aggregates of individual clay particles in which some inert and larger particles may be enmeshed and they are permeated by minute interstices. Between the crumbs there are larger pore-spaces. Thus the soil interstices consist in essentials of a micro-pore-space in the crumbs and a macro-pore-space between them. In this pore-space water moves or is retained under the influence of gravity, evaporation and absorption by plant roots; within it also the soil air, which is richer in carbondioxide, inter-diffuses with the outside atmosphere.

The Capillary tube hypothesis and its failings In their attempts to explain the water relationship of soil, the earlier workers missed the implication of these two sets of pore-spaces. They used the simple fact that the soil was porous and pictured it as a set of capillary tubes: irregular in width, length and direction, it was true, but none the less capillary tubes, to which the simple and familiar tube formulae from pure physics could be applied. The result was the general belief that when the soil moisture content was reduced by evaporation or plant absorption, water was drawn up by capillary attraction from the ground water table to replace it. The hypothesis also gave an apparently sound scientific explanation of the effects of hoeing, harrowing and rolling. This emphasis on the direct association of the ground water table with agriculture persisted in spite of the failure in laboratory experiments to get water to rise more than 3 feet or so even in fine textured clay soils. This difficulty was comfortably dismissed by assuming that the packing of the soil in the laboratory was different from that in the natural field conditions. But experiments conducted over a long period at Rothamsted showed that even after several months of practically continuous evaporation conditions the water level sunk only about 3 feet in the clay soil, about 2 feet in fine sand and just over a foot in coarse sand. The above discrepancy between the experimental results and the original theory could not be easily set aside. Actually the soil-water largely remains *in situ*, as it meets the changes by automatic alterations in the curvature and thickness of films of water about the soil particles. Soil water is resistant to changes and is not drawn from wetter to drier regions, as asserted by the capillary theory.

Some fallacies in drainage and irrigation The failure to understand the role of water in the soil has led to certain erroneous ideas and practices in land irrigation and drainage. In many experiments laid out to determine the optimum quantity of water and spacing between irrigations, it was assumed that the added water distributed itself uniformly throughout a considerable depth of the soil so that the moisture content is everywhere raised from its previous value to a new one. This is not what happens. In the immediate vicinity of the ditch the soil pore-spaces become quickly saturated. The film curvature in the adjacent pores is disturbed and water passes into them from the first set, which are replenished from the water in the ditch. The process continues until all the water in the ditch has entered the soil. At this stage the soil around the ditch is saturated; the volume of saturation depends on the amount of added water and the initial moisture content of the soil. Then there follows a much slower redistribution, in which the saturated cells part with some of their water to emptier cells adjoining the saturated zone, and the action extends back slowly into the saturated zone itself. But this process cannot, over any reasonable space of time, reduce the moisture content to a point lower than a value called the "field saturation capacity," which, for practical purposes, represents the moisture content that the soil can hold against the pull of gravity. So, ultimately, an application of irrigation water wets a certain volume of the soil up to the field saturation capacity. Beyond the boundary of this zone the moisture content may be appreciably less, but appropriate curvatures in the waterfilms will maintain approximate equilibrium between the wetted volume and the adjoining soil.

A 5 ft. depth of freely draining soil holds the equivalent of at least 7½ in. of rain which, with the rain that falls in the growing season, is more than ample for the water requirements of plants. Roots of the common agricultural crops given fair conditions will ramify throughout most of this depth. Remembering that the maximum height of capillary rise, even in heavy soil, is shown by Rothamstead experiments to be only 3 ft., it follows that if the water-table level is lower than 8 ft., the sum of these two values, it is in practice incapable of supplying water to the plant roots. If the water-table level be less than 8 ft. below the surface, it is true that in long droughts the plants may get some of the water. But it is equally true that in wet periods the water-level will often rise into the 5 ft. zone, temporarily checking root activity and causing deterioration in the soil structure. We may therefore take 8 ft. as a fair figure for the critical value of the water-table depth. Soils with a higher water-table than this may well "derive benefit or avoid danger" as a result of new drainage works.

II. SOIL CULTIVATION: ART OR SCIENCE?

Soil tilth The pore-space in the soil is essentially cellular in nature. There are relatively large pores connected together by narrow necks, easily visualised in the case of sandy soils. These pores are the macro-pore-spaces. In the clay soils, aggregates of small particles of clay exist and the aggregates behave like individual particles. There are pores, relatively small, in-between the small ultimate clay particles constituting the aggregates and these pores are the micro-pore-spaces. The pattern of the macro-pore-space between the crumbs and the micro-pore-space inside the crumbs is highly developed in clayey soils. A soil in good tilth—that is in a definite crumb structure—is immediately recognised by the farmer and similarly its converse also—bad tilth, where the structure is destroyed.

Recent researches have led to some interesting conclusions regarding crumb formation: (1) the particles must be less than 0·0005 mm. in diameter, (2) crumb formation is connected with the active or negatively charged spots on the clay and the base exchange capacity of the clay is a measure of this property; (3) these exchangeable ions must be small; (4) Crumbs are formed from the wet clay when the liquid is removed by drying, or by freezing and (5) the crumbs do not form with every liquid. When all these conditions are fulfilled, crumbs will form, the clay particles and the exchangeable ions being held together by water bridges or chains. The water molecules may be regarded as 'bound' to the clay in the sense that in this condition, their properties are somewhat changed from those of water in bulk. Crumbs do not disintegrate when re-wetted and they are known to have a degree of stability.

Stability shows itself in one or both of two forms—mechanical and water stability. By the former we mean the resistance to mechanical forces of rupture such as the pressure of strong winds, the impact of a rain drop, and certain cultivation operations. In general mechanical stability is assured if there is enough colloidal material present. Water-stable crumbs retain their individuality when wetted with water. They will swell and alter their shape, but will not fall down to paste; when the excess water is removed the soil remains in crumb structure Soils which contain exchangeable sodium ions are not water stable.

Rapid drying and rapid freezing produce small crumbs An increase in the salt content of the soil also reduces the crumb size. A study of the crumb structure of soils in natural conditions is one aid in deducing the history of their formation and in classifying them into types and groups.

Weather and cultivation implements as factors in tilth production Cultivation implements have little direct control over tilth production. Their main function is to leave the soil in the best condition for the weather to act or conversely to complete the effect of the weather. The lumps are permeated by lines of weakness already created by preceding weather conditions, and when the harrow teeth, for example, strike the lumps and compress them against one another, they break down along these lines of weakness. To some extent the disc type of implement is an exception in that it does produce more direct disintegration than the standard implements. If owing to unfavourable weather, the soil is in an unkindly condition and seed-bed preparation is behind-hand several harrowings with disc harrow will produce a passable seed bed when other methods would fail. A tilth of this kind is appropriately referred to as a 'forced' tilth.

Ploughing produces a shearing action on the soil and accentuates within the clods any incipient lines of weakness along which disintegration will later proceed; but it does not necessarily produce any considerable comminution at the time. The breaking down of clods to a tilth is connected with alternations of drying and wetting of the soil. The explanation is that during shrinkage the stresses produced when the particles closely approach one another, set up strains within the block which give rise to lines of weakness. The air absorbed on particles' surface in the later stage of drying is evolved suddenly when the block is re-moistened and produces small fissures along the lines of weakness. Thus alternations of wet and dry spells during the winter will shatter down an initially plastic clod of soil into fragments.

Cultivation and the control of soil moisture The operations most concerned are hoeing, harrowing and rolling. The capillary explanation of the function of harrowing and hoeing was that the top ends of the narrow capillary tubes were severed and replaced by the large pore-spaces of a loose soil mulch. The water was therefore unable to travel higher than the bottom of the mulch and thus its evaporation into the air was prevented. There are fundamental objections to this view. In the first place the vast majority of the soils are self mulching i. e., they automatically form a dry surface layer during periods of sustained evaporation. It follows logically that hoeing and harrowing are redundant operations in the direct conservation of soil moisture. In the second place the correct theory of water movement explained already showed that the water films resist movement by adjusting their curvature to suit the changing suction of pressure deficiency. When evaporation occurs from a moist soil the water films at and very near the soil surface become attenuated to a sharper curvature. There will be local readjustment of the moisture distribution in response to the change but little or no upward movement of the water. In sequence water films a little deeper in the soil will decrease in volume and increase in curvature because they part with their water as vapour, which diffuses through the pore-spaces into the atmosphere. The result is that an air dry layer of soil is formed which gradually increases in thickness; below it there is a very narrow transition zone where the film curvature is affected by the high pressure deficiency of the air dry layer immediately above: below the transition zone the moisture films remain relatively unaffected by what has happened above.

The primary function of hoeing is to destroy weeds, which compete with the crop plants for food and water. This competition is much more serious in the early stages of growth than is usually supposed. A secondary function of hoeing and harrowing is of some importance on those soils that form a surface cap or crust when they dry out; in addition to root injuries caused by the contraction of the crust, the large cracks between the clods afford a ready way of escape for soil moisture from below. Cultivation at the time of incipient crust formation will shatter the soil into small pieces and avoid both these dangers. Thirdly, surface cultivation at frequent intervals, by inhibiting the growth of shallow roots, might possibly encourage deeper rooting, but this requires to be tested out.*

The traditional explanation of rolling was that by compressing the top layers of soil it reduced the average size of the voids which were thus able to draw water by capillary action from the larger voids below the compressed layer. However for this action to occur, the moisture content of the soil would have to be so high that no practical man would order the operation for fear of damage to the tilth. The real effect of rolling is to press the soil closer around the roots of the young plants. Alternations of wet and dry weather cause a loosening of the soil and freezing causes the soil to "heave"; both these causes loosen the hold of the young roots on the soil. Rolling presses the soil back into contact with the roots.

In the above explanation of hoeing, harrowing and rolling there is inherent a view of the manner in which the plant roots gain access to soil moisture. The capillary theory conferred on the soil the active role in the duty of supplying the plant with water—that of water moving from higher to lower moisture regions. But in reality the plant roots themselves go in search of the moisture because the adjustment of films of curvature prevent more than a limited movement of soil-water. At the beginning of the growing season moisture up to the field saturation capacity is stored in the soil in the micro-pore-spaces of the crumbs, which can be looked upon as little reservoirs, and in films around the boundaries of macro-pore-spaces between the crumbs. Even a reputedly shallow-rooting plant like barley sends down its roots to 5 ft. below the surface. Hence, the extensive root range of plants and the capacity of the soil to store moisture

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* It might be possible fourthly that the surface cultivation at suitable intervals favours weathering and the conversion of the plant food in the soil into soluble forms appropriate for plant feeding. Possibly also the soil nitrogen and the changes it undergoes in the soil are influenced, *vide* inter-row cultivation effects, pages 294-295. The low nitrogen plots are benefitted by frequent hoeings, but not the high nitrogen plots—in some cases the effects were even negative. (*Ed*).

are complementary functions which together will meet the normal water requirements of the crop.

III. CULTIVATION AND CROP YIELDS

Traditional views in Britain The evidence marshalled justifies the revision of the older views on the relations between the soil and its water content. One conclusion was that *cultivation does not have any important direct effect in controlling the moisture content*, although a great body of tradition asserts the contrary To the practical men, the cultivation was one of the means of growing the best crops, and experiments were started at Rothamsted to prove the obvious—good and thorough cultivation resulted in good crops, and to confirm the views held by practical men: falling off in yields is produced by insufficient cultivation. Slowly, but surely, we have been forced to revise our ideas, for the results have shown that *yields are remarkably insensitive to variations in cultivation.*

RESULTS OF MODERN EXPERIMENTS

Sub-soiling Subsoiling appears to be an unnecessary and unprofitable operation on the Rothamsted soil possibly because the sub-soil although a heavy clay has natural fissures down which surplus water can escape and roots can grow.

Extra ploughing It is generally held that ploughing in autumn and again in spring is desirable in preparing for root crops. Two experiments were conducted and a practical outcome, reinforced by a number of observations later, is that autumn ploughing could be omitted without harm and when given the spring ploughing is seldom needed, at Rothamsted.

Depth of ploughing Deep ploughing has a better effect when the land is weedy. Shallow ploughing is on the average as effective as deep ploughing (Rothamsted results).

Comparison of ploughing and grubbing When the land is not weedy the grubber can replace the plough for a season or so without detriment to the yield. The grubber is not able to control the weeds as efficiently as the plough.

Comparison of ploughing and rotary tillage If the land is clean, as it usually is after a root crop any method of getting a reasonable tilth quickly can be used. The depth of the tilth is not very important provided it is clean. Though yields may be less with rotary cultivation, the reduction is small and may be offset by economy of time and labour.

Degree of consolidation of seed bed Experiments were designed to test whether heavy rolling of a seedbed would have any effect on yield. Rolling improved the stand and early growth, but not the yield. The result showed that quite striking differences in the early growth do not by any means imply that there will be corresponding differences at harvest time.

Intercultivation of root crops With kale, sugar beet and potatoes, the control plots were given the normal number of inter-row hoeings in a number of experiments and the other plots were given extra hoeings. Intensive cultivation produced significant reduction in yield. The extra labour and cost of cultivation were wasted and smaller crop was obtained, in general, in most cases.

Certain experiments were designed to answer the question whether hoeing has any effect on crop yield beyond that attributable to weed destruction. Hand pulling of weeds was compared with hoeing, with two levels of nitrogenous manuring. Hoeing was superior to hand pulling in every case, which would suggest that the operation of hoeing contributes something besides the mere destruction of weeds. Part of the superiority was however due to the hoe being more effective against weeds. Extra cultivation produced increases in yield in the low nitrogen plots; the increases were less in the high nitrogen plots and in some cases even negative (Woburn, Rothamsted and Chertsy results).

American results A number of American results were considered. They were in close agreement with the results discussed above. With the bulk of a large number of experiments, comparing normal cultivation and surface scraping, there was no advantage of normal cultivation over surface scraping. The obvious conclusions are that the general statement that hoeing is beneficial is inapplicable as a generalisation, and that the primary effect of cultivating to produce a soil mulch is in reality weed destruction.

The tradition of good cultivation The extensive discussion given above has covered a wide variety of operations and a wide range of conditions. The results, even on a cautious interpretation, lend no support to the idea that extra cultivations increase crop yield: they show that, provided (a) a reasonable seedbed is obtained, (b) weed competition is prevented during the early growth of the crop and (c) the worst of the weeds are kept down afterwards, then any work in excess is wasted and may even be harmful as far as the crop yield is concerned. On the other hand, they do emphasise the importance of choosing the right time for cultivation.

It may well and rightly be asked, if this be so, how was it that the tradition ever grew up? The following explanation may be provided. The old agricultural system favoured weeds, the implements were clumsy and inefficient and frequent cultivation was the only hope of the farmer; this was possible with the cheapness of labour. Further horses and bullocks used for draught did not cost more, when worked. Even when efficient tools were devised in later years, the old tradition of 'keeping the hoe moving' was maintained. Things have changed; labour is costly; power hauled implements have come to stay in the farm and the more they are used the greater is the running and depreciation charges. There is no place now for cultivation based on custom and tradition. What is necessary should be done, but parsimony as well as extravagance in cultivation are economic blunders in farming today.

Conclusions The bulk of the experiments discussed were done at Rothamsted and Woburn. The practical results were brought to the notice of the farmers by the agricultural press, lectures and addresses. In all these, stress was laid on this central point. No claim is made that many cultivation operations, now accepted as necessary, are a waste of time and money on all soils. It is also urged that in view of the results obtained at Rothamsted and Woburn, other soils should also be examined in a similar manner.

The response to this proposal has been disappointing. Possibly because there is nothing advertisable in our findings and that has a sale value in the market like the improved manures, sprayers, implements, feeding stuffs etc. The change in cultivation technique, the consequent saving in expenditure and their application are subjects for demonstration and education and it is the business of the State, for nobody else can be expected to be interested in the dispersal of such knowledge.

Agricultural research has made vast strides in this century. These also show that generalisations could not be made from a set of results based on one soil, climate, agricultural system etc. The results need not necessarily be valid elsewhere. For rapid changes that may have to be made in post-war agriculture, a reliable basis with field experiments on a national scale would be necessary. This is the immediate need of the day. C. S. K. *(J. Roy. Soc. Arts, Vol. 40 546—579, 1942.)*

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