CRUMB STRUCTURE AND SOIL FERTILITY

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ALL soil research aims, ultimately, at the production of larger and better crops for the better nutrition of our human and animal population. It is, therefore, natural that early efforts were directed towards assessing the fertility of soils through a study of their chemical composition and the availability of plant foods contained in them. The limitations of such methods were soon felt when it was experienced that soils having an adequate mineral content can yet be infertile and that soils apparently similar in regard to their chemical composition and mechanical analysis can show wide differences in yielding capacity. It was then that the importance of air and water for crop growth was adequately realised. Great strides have since been made in our knowledge concerning the physical properties of the colloidal material in the soil. But we have not, as yet, evolved a satisfactory method for giving quantitative characterization to the physical condition of the soil, especially in its natural field state. It may, nevertheless, be stated that so many aspects of soil physics, particularly those having a bearing on some relation between soil air and soil water, are intimately connected with the field structure of soils that studies on the degree of aggregation and the stability of aggregates have contributed largely to a fuller understanding of the processes controlling soil fertility. This emphasis on the structure of soils as a vital factor in their evolution or degradation is, undoubtedly, a great improvement on the older view which merely stated that the soil was deficient in this or that nutrient and that something must be done to restore its level or maintain its supply.

STRUCTURE DEFINED

Structure is a term expressing the arrangement of the individual grains and aggregates that make up the soil mass. The individual grains are the mechanical or textural separates such as sand, silt and clay and are, therefore, the primary soil particles while the aggregates consist of an intimate grouping of a number of primary particles into a secondary unit. The structure of any particular horizon of a soil profile as it appears to the eye of the soil morphologist may be considered as the *macro*-structure of the soil in this layer and refers to the natural arrangement of the soil when in place and undisturbed. Based on the size, shape and character of the faces and edges of these aggregates, terms such as 'nutty', 'mealy' 'granular', 'prismatic', 'columnar', 'platy', 'honey-comb', etc., are used to distinguish between the principal types of field structure[1-3]. Another classification of structure takes into account the structural arrangement of the primary and secondary particles, both in themselves and in a mixture of the two[4]. Several other structural groupings have been suggested such as those based on the type of pore space and the nature of the binding material that is responsible for aggregate formation[5-7]. Agriculturally, however, the kind of structure that is important in its effects, both direct and indirect, upon the soil as a plant habitat is the degree of aggregate formation which resists, under ordinary conditions, the dispersing action of water or beating rain. Aggregation of soil particles into crumbs or granules is the only structure having any practical value and the only one the formation of which has been studied in any detail.

TILTH OF SOILS

By tilth, we understand, ordinarily, the pulverulent condition of the soil which results from successful tillage. A good tilth is a condition which the farmer tries to produce and maintain, when produced, so that it is most suited to the growth of plants. This condition can be recognized in the field by an experienced farmer. Unfortunately, there is, as yet, no single method by which it can be measured quantitatively, for it is the result of many factors which have not been isolated and analysed, but one of the fundamental factors is undoubtedly a good crumb structure. Tilth is closely related to this structure or aggregate formation since both are associated with the presence of colloidal material. Soils devoid of colloids have what is known as single-grain structure, each grain acting as a unit and no compound particles being present. Because of the size of the grains, the tilth of sandy soils is seldom bad. They are well drained, but of course lack the capacity to store moisture or retain plant foods, especially in tropical tracts. Soils containing varying amounts of colloids, on the other hand, present a rather serious problem. The individual grains are so small that if they are forced into a position of close packing, either by mechanical pressure or by the beating action of rain, they become exceedingly hard and impermeable to both air and water. Hence, soils containing appreciable amounts of colloids and with single-grain structure, are the most difficult to manage. Soil husbandry should, therefore, aim at the building up of stable aggregates or crumbs from these single grains.

Structure and Air-Water Relations

For healthy plant growth, the plants must have a continuous supply of soil moisture which does not reach the two extremes of drought and waterlogging. For this condition, two properties of the soil are of great importance: (*a*) the ease with which excess of watter can drain away from a soil under gravity, and (*b*) the amount of water the soil can hold against gravity. These needs are satisfied by the soil having a suitable distribution of pores[8]. If all the pores are large, as in coarse sand, water will drain away freely and air will have easy access to all parts, but if the pores are small, as in silt or unflocculated clays, water will be held in them against gravity and air will enter with great difficulty and the plant will die of asphyxiation. The ideal soil has such a pore size distribution that there are sufficient large pores or *macro*-pores for adequate gaseous exchange to take place between the soil air and the atmosphere and sufficient small pores or *micro*-pores for the soil to hold a reasonable amount of water against drainage for the utilization of plants[9]. This ideal condition of the soil is in part dependent upon the size and arrangement of the soil particles and is mainly controlled by crumb or aggregate structure. In an aggregated soil, the pore space is discontinuous, for the fine pores inside the individual aggregates are usually much finer than those between the aggregates. These pockets of fine pores inside each aggregate act as water reservoirs surrounded by large channels down which surplus water can drain away and so facilitate gaseous exchange between the soil air and the atmosphere.

Flocculation *vs.* Aggregation

Since structure is associated with the colloidal fraction of the soil and since compound particle formation of colloidal materials is usually referred to as flocculation, early students have attempted to approach the problem of soil structure or formation of soil granules by a study of the flocculation of clay soils. While, however, there are instances where mere flocculation of puddled soils have been followed by increased productivity, there is a vast difference between flocculation from the purely colloidal point of view and aggregation from the standpoint of structure. Chiefly, a floccule is stable only as long as the flocculating agent is present whereas stable aggregates are held together by a cementation of the flocculated particles. It is possible that flocculation is an essential first step in the granulation process but there is no doubt that granulation is much more than flocculation, involving as it does a combination of different factors.

Hypothesis of Crumb Formation

The mechanism of the formation of the soil aggregates is one of the most important but hitherto least understood phases of the soil structure problem. The cause of granulation has been variously attributed to the water film, the exchangeable cations, the organic matter, the inorganic colloids of the soil, as also the natural processes of heating and wetting[10]. But, it would appear that the cementation of clay particles at low moisture contents is probably the most important mechanism enabling mineral soils to form crumbs[11].

Crumb and Clod Structure

The difference between the crumb structure and clod structure of a soil is not yet understood, nor has it yet been possible to distinguish them on purely quantitative grounds. It has been assumed that clod structure is produced by purely mechanical means such as cultivation and can be altered at will by such means whereas crumb structure is an inherent property of the soil displayed when conditions are suitable[12].

By ploughing and cultivating a clay soil when wet, huge clods can easily be produced. If these clods are now subjected to a hard frost after the thaw, the clods will have fallen down to small, very stable crumbs so that the land will have lost its clod structure and gained a crumb structure through the agency of the frost[13]. If, on the other hand, these wet clods are dried, they will form hard lumps very resistant to cultivation. So far, the distinction between clod and crumb structure is clear. But if these clods are rewetted under suitable conditions and then carefully cultivated, they will fall down to smaller aggregates and, by continued suitable wetting, drying and cultivation, aggregates of any size can be produced. These aggregates can only be formed by the agency of wetting and drying, cultivation merely hastening the breakdown into suitable aggregates. Again, if the soil were originally ploughed under appropriate conditions, it would break into quite definite aggregates as it was turned in the furrow. This example shows that it is rather difficult to distinguish strictly between crumbs and clods.

The Stability of Structure

Crumbs may have two types of instability: (1) mechanically weak, and (2) unstable in water. If the soil clod does not contain sufficient colloidal material, the crumbs or clods formed in the soil will be mechanically weak and break down very easily to dust by cultivation operations, by the erosive action of the wind or by mechanical shattering through the action of falling rain drops. The last effect is well illustrated by the capping which heavy rain causes on some types of soils. Water-instability of crumbs is in part due to physico-chemical causes. Thus, if the clay forming the crumbs contains much replaceable sodium, the crumbs will be mechanically strong when dry, but will disintegrate when wetted with water, due to the weakening of the cohesion between the individual clay particles forming the crumb. This type of instability often occurs in arid regions, particularly when subjected to irrigation and has caused grave agricultural damage to large tracts of irrigated land.

The water-stability of the aggregates is of the utmost importance in promoting and preserving good structural conditions in the soil. Water may cause a breakdown or deterioration of the aggregates through the process of swelling and 'exploding' of the entrapped air (referred to later), or by mechanical action as with beating rain. The impact of falling rain will have a dispersing action on the aggregation of an exposed soil. These dispersed particles will then be carried into the soil pores causing compaction.

Aggregate Analysis

Aggregate analysis of the soil measures the relative distribution of the various sizes of aggregates and permits a calculation of the percentage aggregation of the finer mechanical separates. Such an expression is really an index of structure though, of course, it does not characterize the type of structure. A large number of methods of aggregate analysis have been proposed and used. In general, three techniques are employed to accomplish such an analysis. They are: wet and dry sieving, elutriation and sedimentation. Russell and Tamhane[12] have recently reviewed the different methods and their limitations. According to them, the aggregate analysis of the soil should be carried out under two conditions of wetting: (1) a slow wetting of the air-dry soil, when the minimum break-up of the larger aggregates takes place and which may represent the inherent water-stable aggregation of the soil, and (2) a rapid wetting of the air-dry soil, which causes a maximum break-up of the larger aggregates and may give the absolute water-stable aggregates. It would, however, appear essential that for obtaining a true picture of the structural capacity of field soils, the samples should not be completely dried or stored for long before making an aggregate analysis.

In the expression of results, the percentage of aggregates greater than 0·05 mm. in diameter has been used to characterize the "state of aggregation" of the soil[14, 15]. This lower limit has been chosen on the basis of the fact that the curves for the aggregate and mechanical analyses intercept near this point, which makes it possible to determine aggregates smaller than 0·05 mm. from the two curves[16,17].

Processes Contributing to Crumb Structure

Inasmuch as the properties of the soil as regards moisture, aeration and heat and, especially, permeability, water capacity and the degree of water penetrability are all greatly dependent upon a good crumb structure, one of the primary functions of soil husbandry will be to create and maintain, when created, a good soil tilth. Two soil properties are important in this connection: (1) the ease with which a soil will form crumbs, and (2) the stability of the crumb structure when formed. Very little is known about the factors responsible for the ease of crumb formation in the soil though, admittedly, soil-forming climatic factors play an important part. Aggregate analysis of a large number of different soils are available which have yielded significant data for a correlation between climate and aggregation[18].

Organic Matter.—Foremost among the other factors contributing to aggregation comes organic matter. It is common knowledge that organic matter serves to aid aggregation in soils. The method of pretreatment with hydrogen peroxide before dispersing soils for mechanical analysis serves to get over the cementing action of organic matter. The exact mechanism of this cementing action of organic matter is little understood. The majority of evidence would appear to point to a kind of adsorption of the humus by the inorganic soil colloids, this adsorption being accompanied by a dehydration which brings about a stable union between the inorganic and organic materials[19-21].

It is not the organic matter itself so much as its decomposition that is important in structure formation[22]. The more rapid the decomposition, the better is the structure[10]. Decomposition of cellulosic materials, such as that resulting from the incorporation of straw into the soil, is especially attended by a marked improvement in structure even though the process of decomposition is very slow. Autolytic products, synthesized by micro-organisms, have a strong cementing action on the soil colloids. It has been suggested that mucus may be the most effective cementing agent[23, 24].

The fertility of humus-rich soils is well known. Indeed, humus is the thing which "makes all the difference between the soil and a mere geological deposit"[25]. It is generally held that every soil, depending on a number of completely interlocked factors, mostly climatic, has more or less definite organic matter level and that, therefore, it is hardly worthwhile to attempt a maintenance of the soil organic matter above certain percentages[26-31]. Recent evidence at Indore would point out, however, that it is possible, by continuous application of bulky organic manures over a period of some years, to raise appreciably the organic matter status of soils as compared to untreated plots; such treated plots are also very high-yielding and possess distinctly better crumb structure[32]. It is, therefore, desirable to carry out tests, under a variety of conditions, whether organic matter content of soils can be built up consistently with economic attainment of high yields.

Crop Effects.—With regard to structure in relation to the growing crops, Russian scientists have studied in considerable detail the effect of different crops on the deterioration and regeneration of soil aggregation[19, 33-35]. Of especial significance has been the result of the relations of grassland systems to soil structure; stable structure is best achieved by temporary ley or grass vegetation[33, 36, 37]. The use of elephant grass in this connection has been described by many workers and found to be of value under East African conditions[38-40]. The dawning recognition of the importance of grass in maintaining a high level of fertility in humid regions is paralleled in semi-arid regions by the recognition of its value in preventing erosion both by affording a dense vegetation cover and by providing a structure which resists erosion when the land is subsequently ploughed. Here, in India, ley farming has not gained any recognition in spite of its importance both in soil rejuvenation and from the point of view of fodder production.

Apart from the particular effect of grassland on soil structure, the mechanism of which is as yet not well understood, all growing crops can affect the structure of soil both indirectly and directly. The indirect effects result from the changes in granulation caused by the increased organic matter produced by plant growth. The direct effects are: "canopy" protection[41] and root influences. The first of these relates to the protection afforded by the leaves and stems against the impact of rain drops by preventing dispersion of the soil. This influence is obviously more effective the denser the foliage and the more rapid the rate at which the protective cover is established. With regard to the influences of root activity on soil structure, we cannot as yet distinguish between the aggregation effects of root pressure referred to later and the binding qualities of root hairs, the production of organic matter, moisture changes resulting from water absorption by the roots, or any possible root excretions. It is quite possible that all these factors operate together in developing granulation and porosity through root influences.

Alternate Wetting and Drying.—Next to organic matter and, from the point of view of natural agencies, even more important in influencing aggregation in soils, is the effect of alternate drying and wetting. Experiments have shown that drying or dehydration of the soil colloids causes a shrinkage of the soil mass and a cementation of clay particles. This dehydration cannot obviously be uniform as unequal strains will arise tending thereby to form clods. When these clods, formed as a result of drying, are wetted slowly, there is a rapid imbibition of water causing unequal swelling throughout the clod and producing thereby fracturation and fragmentation along the cleavage planes[42]. Another, but less well recognized process that follows the sorption of water into the capillaries, results in a compression of the air spaces and, finally, in a "virtual explosion within the clod" as the pressure of the occluded air exceeds the cohesion of the particles[43, 44]. The unequal strain and stress set up by the shrinkage and swelling together with the disruptive action, on wetting, of air entrapped in the pores cause a granulating action on the soil colloids.

Alternate swelling and shrinkage of the soil colloids are also likely to result from pressure effects such as those following the penetration of crop roots or burrowing animals into soil[45, 46]. Due to this pressure, the cementing influences of the water films are probably rendered more effective and the colloidal particles themselves are brought into more intimate contact with each other. The result is, in a soil of good structure, channels left by decaying roots or made by burrowing animals will not collapse but will remain to act as ventilating shafts.

Russian work[47-49] has shown that stable artificial structures can be induced in powdered chernozems and solonchaks by subjecting the soils to mechanical pressure at definite moisture contents depending on the soil properties. The possibility of devising cultivation implements which will perform in the field the mechanical operations which have been shown to produce stable structures in the laboratory requires yet to be explored fully.

It is not, however, always that pressure effects are favourable for structural development. For instance, we know that trampling or excessive cultivation operations, especially on a moist soil, is followed by a deterioration in structure. No quantitative information on the optimum moisture content of soils when pressure effects are most favourable is available and our knowledge of the exact manner in which pressure acts on structure formation is, therefore, difficult to evaluate.

Effects of Cultivation and Tillage.—Culturally, aggregation may be affected in a variety of ways. It is well known that cultivated soils are less granular than the corresponding virgin areas[50]. Tillage affects structure as a result of decreased organic matter production, increased organic matter decomposition, increased leaching, the impact of rain drops on the exposed soil and the mechanical manipulation of tillage implements.

When new land is broken for cultivation, great care is needed to work the soil at proper moisture content. Empirically, the farmer knows that the simplest test in order to determine if the land is fit to plough is to collect some soil just below half the depth at which the plough will work. If it is somewhat difficult to work the soil into a ball in the hand, and, on crushing, the ball breaks into several pieces, conditions are ideal. It is, however, an observed fact that a perfect structure, similar to that of the undisturbed virgin land, cannot be obtained though a structure sufficiently good to meet the demands of a high-yielding crop can usually be maintained.

The importance of working a land at the correct moisture content will be obvious when it is realised that a land badly tilled can show evidence of both waterlogging and drought at the same time. Tillage operations may have varied effects upon soil structure depending upon the nature of the implement and the moisture content at manipulation[10].

Modern science has shown that cultivation operations have only a minor influence on the moisture regime of the soil[51]. In consequence, much of the traditional views on this subject have to be abandoned or recast. At Indore, experiments on shallow *vs.* deep interculture carried out over a number of years have shown that shallow interculture just sufficient to keep down the worst weeds has yielded best and that the adverse effects of excessive interculture are due to loss in structure resulting from constant trampling over the soil.[52] It has been shown, similarly, that preparatory cultivation on the black soils of India[53, 54] and in the Sudan[55] is superfluous and may, at times, be decidedly harmful[56]. Even in temperate and cooler regions, the effect of the traditional thorough cultivation has begun to be doubted[57].

Cation Effects.—Much work has been done on the dispersing action of different cations on the soil colloids. Of practical importance are the effects due to sodium and calcium. The poor structural qualities of alkali soils have been demonstrated more or less conclusively as due to a high concentration of sodium in the exchange complex of the soil. It is equally well recognized that soils in poor physical condition can be restored to good tilth if the sodium ion is replaced by calcium ion. These facts along with laboratory observations that clay suspensions can be flocculated by calcium salts, have led to the widely accepted view-point that the beneficial effects of lime are due to its ability to flocculate the soil colloids. But experimental evidence upon the effect of calcium ion on the physical properties of the inorganic soil colloidal fraction does not altogether support the view that calcium favours aggregate formation. Thus, it has been found that granulation is not correlated with the degree of saturation of the soil with calcium and that the calcium ion is in no way better than the hydrogen ion[58, 4]. It has even been reported that the hydrogen system is more favourable to granulation than the calcium system[59] and that lime has a dispersing action on soil aggregates[60]. Recent researches would appear to point out that the effect of calcium upon aggregate formation is only indirect through its promoting micro-biological activity and consequent increased production of humus[61-63, 21].

The cementing materials in some soils may be iron hydroxide[64] but nothing is known with precision. This is especially true in lateritic soils that are known both for their high degree of aggregation and for their large iron content[65]. It is also possible that colloidal alumina may play a rôle similar to that of iron in aiding aggregation and in affecting, generally, the physical behaviour of soils.

Effects of Manures and Fertilizers.—The beneficial effects of manures upon granulation and aeration have been dealt with before; little is known concerning the effects of fertilizers. Continuous use of artificial fertilizers over a period of years has been known to result in a marked degradation in soil structure[66]. It has been experienced that superphosphate application in eroded fields aids in the improvement of structure; it is as yet difficult to conclude whether this effect is only due to the gypsum component of this fertilizer[67]. It is essential to recognize in this connection the complex relationships that are involved upon manure applications to the soil and the rather varied results obtained by different workers relative to the effects of manures on soil structure[33, 34, 68, 69]. Indirectly, however, all fertilizers will, as with manures and lime, have a large influence in the preservation of structure through increased foliage and root production.

Effects of Drainage, Waterlogging and Irrigation.—Proper drainage is followed by increased aeration, greater root development, more intense bacterial activity and the promotion of oxidation processes. The combined effects of these factors will normally lead to better granulation while their absence will be accompanied by deterioration in structure.

The breakdown of aggregation in the surface during irrigation leads to crust formation which produces unfavourable air and water relations for plant-growth[33]. Hence, the effect of irrigation water, especially in arid regions, on the structure of the surface soil is similar to that of natural rain in humid regions unless, of course, water-stable aggregates are present in the surface layers. In addition, irrigation waters containing unfavourable concentrations of soluble salts will have their deleterious effects on structure[70].

Importance of Structure for High Yields

From the foregoing, it is perhaps reasonable to expect that aggregate analysis may well become, in the near future, a soil characteristic of considerable importance. The agricultural significance of structure lies in its promoting (1) the capacity to absorb and retain moisture, (2) resistance to erosion, (3) free drainage and absence of waterlogging, and (4) easy workability. A combination of these factors will normally lead to greater productivity so long as plant food is adequate. On the contrary, common observations have often revealed that soils apparently rich in fertility elements have not always been highly productive. At Indore, the positive effect of a manurial or a cultural treatment observed in one experiment on a particular field has very frequently been negatived in the same season on another[71]. It soon became apparent that the difference was mainly due to the existence, in reality, of two different types of fields, one well drained and the other, eroded and waterlogged. The average yields of seed cotton for the two types of fields over a period of years were approximately 414 lbs. and 194 lbs. per acre respectively. The results of manurial trials during different seasons have shown that, with few exceptions, both artificial nitrogenous fertilizers and organic manures produce a good response on the well-drained fields and a very much smaller or no response from poor fields[72]. This, at first sight, appeared contrary to the general expectation that poor soils should be more responsive to manuring than rich ones. When closely examined, however, these results showed that poor fields were often characterized not so much by a deficiency of essential nutrients as by a loss in structure resulting from impeded drainage and waterlogging.

Another interesting and characteristic difference exhibited between well-drained and badly drained or eroded fields has been in respect of the nature and extent of their surface cracking during summer fallow. It has been possible to make a quantitative measure of the amount of cracking in different fields. The results have shown that cracking is deeper and more extensive in a good field as compared to an infertile field[73].

These results only emphasize the importance of restoring structural conditions of the surface soil before crop yields can be enhanced by suitable manurial applications. Soil conservation depends essentially on the amount, kind and stability of the soil aggregates and the problem of improvement of eroded land for successful crop-growth resolves, therefore, into one of restoring structure[74]. Some preliminary results have shown that, for the black cotton soil, an economic way of achieving this will be by keeping the sub-surface soil in a poor field open by dressings of lightly fired soil; not only increased yields are obtained without manuring, but response to manures is also greater on soils so treated[75].

To sum up, plants require, in addition to nutrients, air and water for growth. In the absence of adequate amounts of moisture, plants cannot utilize soil nutrients and carry on their normal physiological functions. The growth of plant roots and the germination of seeds require favourable air conditions for respiration. Moreover, a small root system restricts the soil volume in which nutrients are available for the plant. Lack of sufficient air and water also affects bacterial activity and the very necessary aerobic biological processes are greatly hindered.

The air-water relations of the soil are dependent upon structure. While a good deal of work has hitherto been achieved on the relation of soil nutrients to crop-growth, only inadequate attention has been given to providing a favourable soil-air-water environment to the germinating seed and the growing crop. Recent developments in soil structure problems have made it possible to define more or less precisely what was only vaguely recognized hitherto as tilth. Future work should aim at fully utilizing this knowledge gained in regard to the significance of soil structure for maintaining or restoring soil fertility.

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SOME POST-WAR PROBLEMS OF JUTE

BY

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CONSUMPTION of jute has been considerably reduced owing to the war. Although jute is an important raw material for the war, its use for war purposes has not been sufficiently large to offset the fall in civilian consumption. This may be seen from the following table:—

World Consumption of Jute

(Lakhs of bales of 400 lbs.)

Season July—June	Consumption
1936-37	126
1937-38	113
1938-39	110
1939-40	113
1940-41	79
1941-42	88

In the third year of the war, the total consumption of jute fell by about a quarter of the pre-war consumption. The reduction in civilian consumption must have been much greater than this. Though no precise estimate of it is possible for want of relevant information, a few facts are noted in this connection.

Exports of raw jute and jute goods to the enemy and enemy-occupied countries, which in peace-time accounted for about 30 per cent. of the total world demand, have been completely stopped. In 1941-42, about 11 lakhs of bales of jute were consumed in India for war purposes. In the United States the civilian consumption of new jute bags has been reduced to half that of 1941, while the Government there is building up a large stock pile of raw jute and burlap from the available supply in the country. If the jute requirements for war purposes of the other Allied countries are also taken into consideration, it may not be wide off the mark to say that the total civilian consumption of jute (excluding secondhand products) is at present about half the pre-war consumption.

Thus the main problem of jute in the post-war period will be to increase its consumption to double the present rate of civilian consumption. The solution of this problem is dependent on a number of factors, some of which will be discussed below.