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Field Structure of Cultivated Soils with Special Reference to Erodibility by Wind[1]

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ABSTRACT

A study of structure and erodibility of soil by wind was carried out on wind eroded and residual soil materials in a condition usually existing in the field and after sampling, cultivating, and dry sieving.

Field structure and erodibility of soils varied greatly with as little as 1 inch of simulated rainfall. In soils undisturbed by cultivation after rain, four distinct phases of structure were found, all of which possess different degrees of erodibility by wind. These phases are the primary aggregates (water-stable aggregates), the secondary aggregates (granules and clods), the surface crust, and the consolidated soil material between the secondary aggregates.

The abrasive action of wind erosion was shown to be one of the most serious aspects of erodibility by wind.

The mechanical stability, that is, the resistance of a soil to breakdown by mechanical forces such as cultivation or sieving, was found to vary directly with the resistance of the soil to abrasion by wind-blown sand. Mechanical stability was greatest for drift particles (sand grains and water-stable aggregates mostly), less for the secondary aggregates, followed in order by the surface crust, the consolidated materials between the secondary aggregates, and lastly the consolidated materials, if any, which held drifted particles together after they were wetted and dried.

The amount of dispersed fine silt was found to be a primary factor influencing the formation of the surface crust and the consolidation of the soil body after it was wetted and dried. A fraction of clay size, being much less dispersible than silt, was found to be the primary factor of secondary aggregate forma-

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tion. Water-dispersible silt and clay were responsible in large measure for the resistance of the soil to erosion by wind. Although the amount of erosion was limited to some degree by the presence of water-stable aggregates too large to be moved by wind, it was found that cultivated dryland soils lack these aggregates in sufficient amounts. The resistance of these soils to wind action was found to depend primarily on their ability to form secondary aggregates, or clods.

The secondary aggregates preserved their identity below the surface even after repeated wetting and drying in the field. It was concluded, therefore, that the physical condition of the soil is indicated as well or better by methods such as dry sieving, which primarily measure the state of the secondary aggregates, than by methods that measure the state of the primary aggregates.

FRESHLY cultivated soils are composed of a more or less loose mixture of particles and aggregates of widely variable dimensions. These may range from large clods several inches in diameter to particles of dust. Erodibility in such a condition is dependent primarily on the proportion and bulk density of erodible fractions contained in the soil when it is dry (3). Only dry soil materials are eroded by wind.

An entirely different regimen of conditions exists in a cultivated soil after it has been wetted by rain and dried. A surface crust is almost invariably formed due to impacts of raindrops on the ground. Often the crust is hardly discernible but has a profound influence on erodibility. Except at the immediate surface, the primary (water-stable) aggregates and the secondary aggregates, including clods, usually undergo little transformation by individual wetting from rain and drying. A greater change occurs in the degree of compactness and cementation between the various recognizable aggregates. This type of cementation has an important influence on erodibility by wind, but the degree of cementation is generally too weak to be detectible by wet or dry sieving. Thus, wet or dry aggregate analyses based conventionally on sieving or elutriation in water or air omit entirely some important aspects of soil structure. A study was conducted to gain more specific information of the various phases of soil structure common to cultivated soils in the field and how these phases relate to erodibility by wind.

Procedure

Composite samples of soil when in a dry condition were taken from 1 to 2 inches of depth from wind-eroded fields and from freshly accumulated drifts within or near the eroded fields. Four fields were chosen, all from the black soil zone, representing Lancaster sandy loam, Crete silt loam, Rokeby silty clay loam, and Sutphen clay. Henceforth, the soil will be referred to by textural class only.

Samples from the freshly accumulated drifts, still unaffected by rain, represented that portion of the soil which had been moved about by the wind and deposited against obstructions or traps, such as weeds, fence rows, or road ditches. Henceforth for convenience, soil material obtained from these drifts will be referred to as drifted soil material and soil material obtained from the wind-eroded fields as residual soil material.

Determinations were made of the physical soil characteristics which might have had some bearing on erodibility by wind. These determinations included mechanical composition by the method of Bouyoucos (1), the size-frequency distribution of water-stable particles and aggregates by the method of Yoder (9) modified in accordance with the latest Soil Conservation Service recommendations, the size-frequency distribution of dry aggregates and their mechanical stability by the rotary sieve method (4), and the amounts of erosion determined in the laboratory wind tunnel used regularly in this work.

To measure the amount of erosion the soil was placed in a porous-bottom tray 5 feet long, 8 inches wide, 2 inches high, and exposed to wind until soil movement ceased. The wind had a drag velocity of about 1.4 miles per hour and a velocity of about 25 miles per hour at a 6-inch height. The amounts of erosion from trays placed parallel with the direction of the wind were determined under three sets of conditions: (a) exposing well-mixed dry soils to wind; (b) exposing to wind after consolidating the soil by spraying with 1 inch of water and drying, and (c) exposing to wind and to sand abrasion after consolidating the soil. Fine dune sand was used as abrader and was placed in a tray immediately on the windward of the tray that contained the soil.

The surface crusts, caused by spraying, were tested for abradability by dune sand and also for resistance against breakdown by sieving. The crusts were scraped off gently with a spatula when the soil was dry and sieved on the rotary sieve.

Another series of tests was conducted to determine more conveniently the abradability of the different structural units of the soil. In these tests small volumes of clods 1/4 to 1/2 inch in diameter and cylindrical blocks of soil were exposed to abrasion by dune sand. The clods or blocks of soil were placed on the leeward of the tray containing the abrader. The clods were placed to cover the bottom of a trough sloping into the direction of the wind. The vertical cross-sectional area of that surface of the clods exposed to abrasion by dune sand was the same as that of the cylindrical block of soil. The amount of abrasion was determined by weighing the clods or block of soil before and after exposure and adding to this difference the weight of the soil fragments greater than 0.42 mm that were broken off the clod or block and lodged at the foot of it. The amount of the soil fragments greater than 0.42 mm was determined by sieving.

Consolidation of soil blocks, which were 2 inches in diameter and 2 inches high, was accomplished by placing a soil in a waxed paper cylinder with open top and bottom and spraying the top of the soil with about 1 inch of water, followed by drying. Wetting and drying was repeated several times in some cases. In every case the consolidated soil, even when composed of almost pure sand, held together without crumbling.

Finally, the degree of dispersion of the various fractions of the soil in water was determined. Air dry soil was immersed in water in a vacuum and the bottles containing the soil and the water were turned end over end at the rate of 30 turns per minute for 2 minutes. The percentage of particles smaller than 0.02 mm contained in suspension was determined by the hydrometer method.

Results

SIZE AND NATURE OF SOIL FRACTIONS TRANSPORTED BY WIND

Dry soil fractions transported by wind and deposited in drifts in the vicinity of the eroded fields were generally smaller than 0.84 mm in diameter (table 1). A few fractions exceeding this diameter were mainly organic fragments, considerably lighter than the mineral particles or aggregates.

It will also be seen from table 1 that soil materials deposited in the drifts contained much less dust smaller than 0.05 mm in diameter than corresponding soil materials from the eroded fields. Evidently much of this fine fraction was carried away from the vicinity of the eroded fields and only a portion of it was deposited in the drifts.

Although the residual soil materials contained some water-stable aggregates too coarse to be moved by wind, the amount of these in the soils studied was relatively small. A great percentage of the water-stable aggregates was of a size readily erodible by wind (table 1).

The erodibility of well-mixed, freshly cultivated soils (condition (a), table 1) varied with the amount of erodible fraction contained in the soil. In sandy loam and silt loam the erodible fraction was predominantly smaller than 0.42 mm in diameter, but in the finer textured soils a considerable proportion of particles from 0.42 to 0.84 mm in diameter also constituted an erodible fraction (table 1). Clay had the highest pro-

Table 1.—Physical properties of wind-eroded (drifted) and residual soil materials.

Soil class	Soil material	Dry fractions >6.4 mm	6.4–0.84 mm	0.84–0.42 mm	0.42–0.05 mm	<0.05 mm	Water-stable fractions >0.84 mm	0.84–0.42 mm	0.42–0.02 mm	<0.02 mm	Amounts eroded* (a)	(b)	(c)
		%	%	%	%	%	%	%	%	%	Tons/ac.	Tons/ac.	Tons/ac.
Sandy loam	Drifted	0	0.2	2.5	92.6	4.7	0.3	0.9	92.6	6.2	—	—	—
	Residual	21.1	22.8	13.7	24.0	18.4	9.6	9.6	70.4	10.4	3.4	0.4	13.0
Silt loam	Drifted	0	1.0	12.3	84.0	2.7	0.4	4.1	84.1	10.2	—	—	—
	Residual	24.8	14.5	19.9	27.6	13.2	4.4	17.0	61.8	16.8	4.5	0.2	5.6
Silty clay loam	Drifted	0	1.7	29.0	65.5	3.8	0.7	10.5	78.4	10.4	—	—	—
	Residual	19.9	15.6	25.3	31.4	7.8	3.2	14.4	67.0	15.4	2.9	0.3	9.4
Clay	Drifted	0	2.4	43.4	52.5	1.7	1.0	29.0	65.1	4.9	—	—	—
	Residual	0.4	13.1	45.5	37.9	3.1	2.6	37.8	50.0	9.6	9.5	3.4	11.0

*Conditions described in "Procedure."

portion of erodible fractions ranging from 0.42 to 0.84 mm in diameter, and these fractions apparently contributed greatly to the high erodibility (9.5 tons per acre).

INFLUENCE OF SOIL CONSOLIDATION AND OF ABRASION ON ERODIBILITY BY WIND

The application of 1 inch of water sprayed on the soil followed by drying (condition b, table 1) produced a surface crust and a cementation of the soil body which greatly reduced the erodibility by wind. The crust was easily recognizable by its dense, platy structure. This type of structure became less distinct with depth till it merged with the mass of soil below at a depth varying to ¼ inch, depending on the soil. The most tenacious crust and the greatest degree of cementation below the crust was on silt loam and silty clay loam. A thin, fragile crust was formed on sandy loam and a thicker but even more fragile one on clay. Consequently, the greatest proportional reduction in erodibility due to soil consolidation was on silt loam and silty clay loam, less on sandy loam, and least on clay.

The amount of erosion increased greatly when a stream of dune sand was blown over the consolidated soils in a dry state (condition c, table 1). The cutting, grinding, and impact action of sand disintegrated the surface crust and some of the consolidated material below the crust into particles small enough to be moved by wind. This type of structural disintegration is known as abrasion and is a very important phase of the wind erosion process on all soils (3). There are two main aspects of abrasion: One is the disintegration of nonerodible or consolidated soil units into particles small enough to be moved by wind, and the other is the wearing-away of erodible soil units into dust capable of being carried away from the vicinity of the eroded region. Methods of measurement described herein are designed primarily to measure the former aspect which, from the standpoint of wind erosion control, is perhaps a more important aspect of the abrasion process.

On the whole, the consolidated sandy loam was most subject to abrasion. Clay had a very fragile crust which wore off readily under abrasion, but dry clay aggregates were extremely resistant to abrasion. Silt loam and silty clay loam had a surface crust most resistant to abrasion, yet their aggregates showed a moderate degree of resistance to abrasion.

It was evident from these preliminary tests that the different phases of soil structure in a dry state possess different degrees of abradability. A study was continued to find possible relationships between the physical properties of the different structural units of the soil and their abradability.

MECHANICAL STABILITY AND ABRADABILITY OF DIFFERENT STRUCTURAL UNITS OF WIND-ERODED AND RESIDUAL SOILS

A separation of some structural units of the soil by sieving in a dry state was necessary to study more conveniently the abradability of these different units. All of the structural units broke down somewhat under sieving, but in various degrees. The rotary sieve was used for this purpose.

The breakdown of clods and other structural units of the soil by sieving varied directly with the abradability of these fractions (figure 1). Thus, the loosely consolidated blocks of wind-eroded particles obtained from fresh drifts were most subject to breakdown by sieving and also to breakdown by abrasion with dune sand. Blocks of the same sieve-fraction from residual soils were less subject to breakdown by sieving and also by abrasion with dune sand. Dry clods were much less subject to breakdown by sieving and also much less subject to disintegration by abrasion into particles small enough to be moved by wind.

The resistance of the soil to breakdown by mechanical forces, such as sieving or abrasion by drifting sand, is known as mechanical stability. The mechanical stability is a relative measure of coherence or strength of cementation between or within the particles or soil aggregates in a dry state and, as used in this study, is equal to $100\,\frac{W_1}{W}$, where W is the weight of individual particles or aggregates, or the weight of a consolidated body of these units before sieving and W_1 is the weight after the sieving. The speed of disintegration of the individual particles or aggregates measures the strength of cementation *within* these units; the speed with which consolidated bodies disintegrate to individual structural units is a measure of cementation *between* these units.

A study of the abradability of bodies or blocks of soil by wind-blown soil grains showed that the soil body is composed of several different types of structural units having widely different degrees of mechanical stability or coherence and, consequently, of resistance to abrasion by wind-blown soil grains. Soil grains blown into drifts by wind had the greatest mechanical stability and, therefore, were least susceptible to abrasion (table 2). As shown in table 1 these grains were, in the main, water-stable aggregates and individual sand grains. Virtually complete resistance to breakdown by sieving was exhibited by wind-eroded sand grains common in sandy loam soil and by aggregates from clay. A somewhat lower mechanical stability was exhibited by wind-eroded units (mostly water-stable aggregates) from silt loam and silty clay loam.

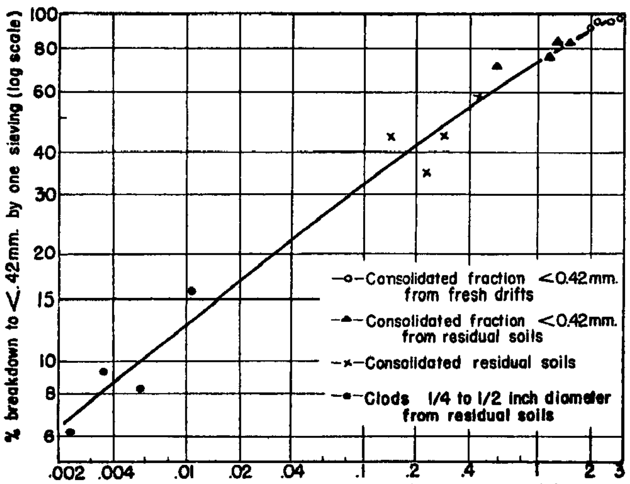

FIG. 1. — Relation between degree of breakdown of blocks of soil by sieving and their susceptibility to abrasion by wind-blown sand.

The dry nonerodible granules and clods obtained by sieving of residual soils were next in order of mechanical stability (table 2) and in resistance to abrasion by wind-borne sand (figure 1). The mechanical stability and resistance to abrasion of these aggregates varied directly with the fineness of soil texture. This order was not the same for all the structural units of the soil, however. One gram of dune sand wore off from 0.002 to 0.01 gram of the dry aggregates into particles smaller than 0.42 mm in diameter, depending on soil texture.

The surface crust had a mechanical stability and resistance to abrasion considerably lower than that of dry granules or clods (table 2). The crust on clay and sandy loam had the lowest mechanical stability and that on silt loam the highest. The abradability of the crust varied inversely with its mechanical stability, being highest on clay and sandy loam and lowest on silt loam. A typical appearance of abrasion of the surface crust by impacts of wind-blown sand is indicated in figure 2.

Table 2.—Mechanical stability of structural units of wind-eroded and residual soil materials.

Structural units	Mechanical stability			
	Sandy loam	Silt loam	Silty clay loam	Clay
	%	%	%	%
Fraction >0.42 mm. from fresh drifts	97.6*	95.5	95.0	97.0
Dry aggregates and clods >0.42 mm	83.8	91.7	90.6	93.8
Surface crust ⅛ to ¼ inch thick	60.2	73.2	69.3	58.5
Fraction <0.42 mm. from residual soil, consolidated	17.0	28.1	27.3	17.4
Fraction <0.42 mm. from fresh drifts, consolidated	3.0†	8.8	5.0	4.6

*Mostly sand grains.
†Cementing strength between particles was barely overcome by wind having a drag velocity of about 1.4 miles per hour.

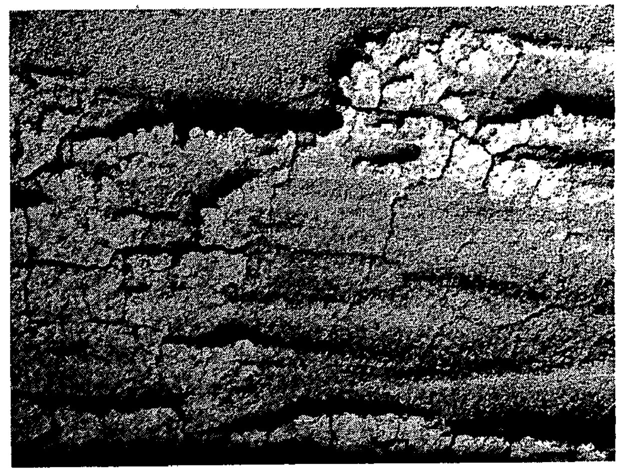

FIG. 2. — Surface crust on clay soil partly destroyed by abrasion with dune sand. Duration of abrasion: 5 minutes under a velocity of 25 miles per hour at 6-inch height.

Some loose erodible grains (sand grains and water-stable aggregates) were found on the surface of all soils after they were sprayed thoroughly with water and dried. It is evident that some of the finer particles of

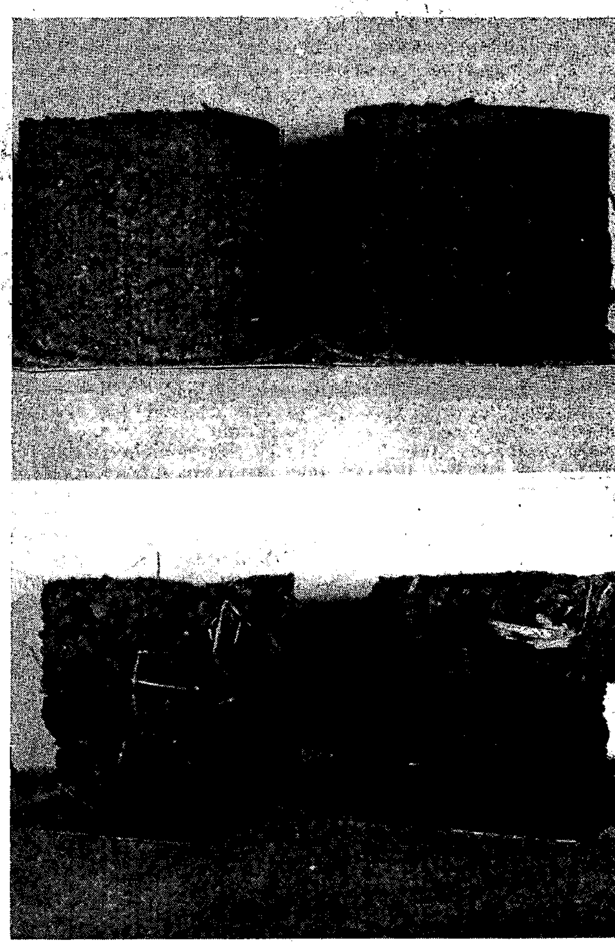

FIG. 3. — Blocks of silt loam (left) and sandy loam (right) consolidated by spraying with 1 inch of water 4 times and drying after each wetting. Upper row: before abrasion by dune sand; lower row: after abrasion for 45 seconds, during which period about 210 grams of sand struck each block. Note the exposure of the originally embedded, less abradable soil aggregates after abrasion. These are primarily secondary aggregates, or clods.

the size of silt and clay were washed down, leaving some coarser grains loose on the surface crust. These loose grains moved readily in saltation and caused some abrasion of the surface crust, the amount of abrasion depending on the amount of the grains, the mechanical stability of the surface crust, and the distance that the grains moved along the ground. Even with a distance as short as 5 feet, it was evident from casual observation that the amount of abrasion of the surface crust was much greater on the leeward than the windward end.

Next in order of mechanical stability and resistance to abrasion was the consolidated material initially composed of fractions smaller than 0.42 mm in diameter (table 2). These fractions are highly erodible if unconsolidated and are found in various amounts between the coarser granules and clods. The cementing force or cohesion between these particles in a consolidated state, as for the surface crust, was least in clay and sandy loam and greatest in silt loam soil. Consolidated bodies composed of these fractions disintegrated at a relatively high rate under impacts of abrasion by dune sand, 1 gram of the abrader wearing away from 0.6 to 1.5 grams of the consolidated material, depending on soil texture (figure 1). Thus, the rate of abrasion of these consolidated bodies was 150 to 300 times as great as that of granules and clods.

Blocks of consolidated soil composed of all structural units common in cultivated soils abraded very unevenly (figure 3). After a short duration of exposure the granules and clods began to protrude into the air stream indicating that after wetting they were merely embedded in the fine, loosely consolidated portion of the soil. The strength of cementation between the aggregates was much lower than that within these aggregates, hence the reason why consolidated blocks of soil abraded so unevenly.

Last in order of mechanical stability and therefore of resistance to abrasion were the consolidated bodies composed of particles less than 0.42 mm in diameter drifted and deposited into dunes by wind (figure 1 and table 2). The rate of abrasion of these consolidated bodies was from about 300 to 1,000 times as great as of granules and clods. It is evident that the cementing material capable of holding these particles together after consolidation, thereby resisting erosion by wind, was partly removed in the form of dust < 0.05 mm in diameter (table 1). The data in table 1 show also that there was a considerable removal of water-stable fractions < 0.02 mm from the soil material drifted and deposited into dunes by wind. It is apparent that these particles were the cause of strong cementation found between the secondary aggregates or clods.

To determine the influence of these fine water-stable fractions on soil structure, soils were immersed and shaken in water for 2 minutes and the particles smaller than 0.05 mm in diameter were removed by repeated decantation after appropriate periods of settling. The water-stable grains or aggregates greater than 0.05 mm were then dried. There was virtually no cementation between the water-stable aggregates after blocks of these were wetted and dried. The water-stable aggregates from all soils acted much like sand grains in that they failed to cohere to each other. It is apparent that the finely dispersed fraction of the soil is to some degree responsible for holding these water-stable fractions together to form secondary aggregates or clods.

Discussion and Conclusions

The study indicates that the great majority of the water-stable aggregates contained in Chernozem soils are of the size readily eroded by wind. Since the water-stable particles or aggregates represent the more stable structural units to which the soil may be disintegrated in the field, it may be expected that the increase in their size will increase the resistance of the soil to wind erosion. The problem is how to create enough of the water-stable aggregates sufficiently large to resist the wind.

The resistance of these soils to wind erosion is dependent consequently on their ability to form what may be considered as secondary aggregates, that is, coarse granules and clods. In fact, emergency methods of wind erosion control are based principally on methods of tillage that leave the soil surface rough and cloddy.

The formation of secondary aggregates is shown from this study to be due in large measure to the amount of water-dispersible cements. Tillage, pressure at depth, repeated wetting and drying, and time probably all influence the dispersion of soil cements and contribute to the formation of secondary aggregates or clods. Since many soils undergo frequent wettings in the field it has been assumed that a useful measure of soil aggregation would be found by sieving the soil in water rather than in the air (8). The secondary aggregates or clods were thus considered as a transient mass that slakes with repeated wetting and drying. This study shows, however, that a clod, the same as any other structural aggregate, is "transient," but only in degree. Individual rains are shown to have little influence on the form or compactness of clods below the surface. The identity of these secondary aggregates is more or less preserved even after repeated wetting and drying in the field. Therefore, the field structure of soil is indicated as well or better by methods, such as dry sieving, which primarily measure the state of the secondary aggregates, than by methods that measure the state of the primary aggregates. Only within a narrow zone of the immediate surface do the secondary aggregates become appreciably disintegrated by impacts of raindrops where the soil mass assumes a structure different from that below.

This study shows that the formation of secondary aggregates is due primarily to the proportion of water-dispersible soil particles of the size of clay, perhaps of both mineral and organic origin, obtained when the aggregates are shaken in water. When this fraction together with dispersed silt is removed from the soil, the water-stable aggregates of which the secondary aggregates are composed remain loose much like individual sand grains. Russell (6) affirms that micro-aggregates (water-stable aggregates) ". . may be considered as units *from which clods in arable soils are built-up.*" This study shows that the micro-aggregates are virtually incapable of forming the secondary aggregates or clods unless a certain proportion of cementing fraction of the size of clay is dispersed among these aggregates.

The importance of secondary aggregates in soil structure formation is not fully recognized in agricultural research. For example, a recent review on soil aggregate formation (7) fails even to mention the secondary aggregates, and the whole thesis of soil structure formation is based on the unfortunate assumption that the status of the water-stable aggregates as conventionally determined by sieving, elutriation, or sedimentation in water is a proper index of soil structure. However, soil structure as it exists in the field is a complex condition. Consequently, no single method can be used to evaluate it completely.

Primary and secondary aggregates are phases of soil structure common under field conditions. There is yet a third phase that assumes major importance with respect to erodibility by wind and, no doubt, also with respect to soil tilth and probably to erodibility by water. This third phase is concerned with cohesive forces that are exerted *between* the secondary aggregates after the soil has been wetted and then dried. The degree of cementation between the secondary aggregates varies greatly, as within the aggregates, depending on the number and the nature of wettings and on the physical-chemical nature of the soil.

The degree of cementation between the secondary aggregates after the soil has been wetted and dried is due in large measure to the amount of particles of the size of silt and clay dispersed by the wetting. Dispersed silt, although usually not considered as a soil cement, acts as a weak cement after the soil is wetted and dried. Silt disperses in water much more readily than particles of the size of clay. The presence of large amounts of dispersed silt particles in a soil appears to cause the formation of a compact, massive structure which, while quite resistant to wind erosion, may present a serious structure problem otherwise. Bradfield and Jamison (2) conclude that hard and intractible soils are usually those largely composed of fine silt having a single grain structure when dispersed in water. Kaspirov (5) further concludes that the main factor in crust formation is the presence in soils of water-dispersible particles less than 0.01 mm in diameter, regardless of the amount and quality of humus or the amount of salts present in soil solution. The present study confirms the above conclusions.

It is generally recognized that soil possessing a well-developed water-stable structure is much more resistant to water erosion than one with a poorly developed water-stable structure (6). Resistance to water erosion is probably primarily determined by soil permeability. The determining factor of resistance of soil to wind erosion, on the other hand, is the size of dry aggregates large enough not to be moved by the wind. Many soils that have a well developed water-stable structure are extremely erodible by wind because the size of the aggregates is, on the whole, too small to resist the wind. Mineral soils resistant to wind erosion generally contain more than 60 per cent of dry aggregates greater than 0.84 mm in diameter as determined by dry sieving, regardless of whether these aggregates are stable in water or not.

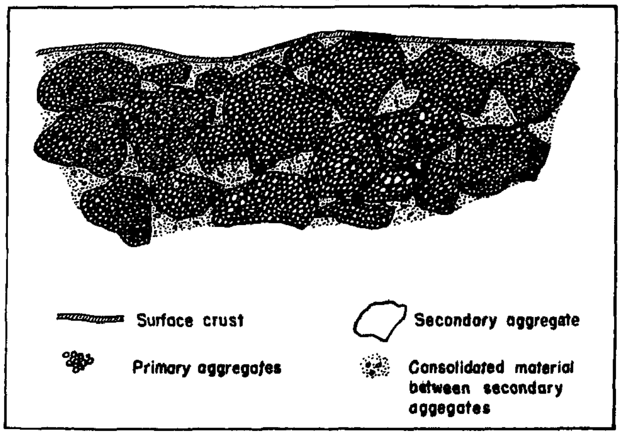

FIG. 4. — Diagrammatic representation of field structure of soil.

The fourth phase of field structure in cultivated soils is the surface crust, which results principally from the beating action of raindrops on the ground. It creates conditions of the soil surface, some of which tend to reduce and some to increase erodibility by wind. The beating action of raindrops consolidates some of the erodible soil fractions and tends to reduce erodibility. At the same time it tends to smooth the soil surface and this tends to increase the erodibility. The raindrop action also tends to leave some soil grains or aggregates loose on the surface. These grains are readily moved in saltation and under certain conditions cause considerable abrasion of the surface crust. The various phases of field structure in cultivated soils are shown diagrammatically in figure 4.

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