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# SEDIMENTARY CHARACTERISTICS OF DUST STORMS: I. SORTING OF WIND-ERODED SOIL MATERIAL

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ABSTRACT. Sorting of soil materials by the wind is an intricate phenomenon. The most distinct feature in the whole sorting process was found to be the peak diameter of the saltating grains. Fractions larger than the peak diameter tend to remain in the wind-eroded fields, and particles smaller than this diameter tend to be deflated and carried far through the atmosphere. Depending on soil class, from 31 to 78 percent of particles smaller than 0.1 mm in diameter contained in the wind-transported soil fraction are deflated by a single windstorm. Silt generally is more readily deflated than sand or clay. Wind *erosion has caused little change in texture of loess soils but has tended* to remove the fine constituents from the coarser-textured soils, leaving the sand behind. This sorting process if continued even for a day or two adds considerably to the general sandiness of the affected areas and to consequent irreparable depletion of soil productivity.

## INTRODUCTION

An eroding wind acts on the soil like a fanning mill on grain—removing the finer and more porous particles and leaving the coarser and denser behind. There is a wide range of rates of removal of different soil fractions. Some fractions are not moved at all; other fractions are moved slowly by surface creep; some are transported rapidly in saltation; and still others are carried through the air in suspension. A substantial amount of study has been made by Bagnold (1943) on the grading of sand by wind, but only preliminary information is available on the sorting action of wind on arable soils (Fly, 1935; Daniel, 1936; Chepil, 1946). A series of studies was undertaken, therefore, on the sorting of various soils by wind, on the atmospheric concentrations of dust and rate of dust removal from present-day wind-eroded regions, and on the composition of dust originating from different soils. The first of these was on the intricate phenomenon of the sorting of soil materials by the wind and on effects of the sorting process with respect to possible changes in the productivity of agricultural lands. The results of this study are reported herein.

## PROCEDURE

Samples of soil when in a dry condition were taken to about one-inch depth from wind-eroded fields, from coarse eroded materials deposited in surface depressions of the fields, and from newly accumulated drifts within or near the fields. Five individual samples collected from different parts of each field were combined, oven-dried at 175°F, and thoroughly mixed. The samples of drifted material represented that portion of the soil moved primarily in surface creep and saltation and deposited in or near various obstructions or traps such as vegetation and ground depressions during a single windstorm. The individual samples were taken from different positions on the drifts to assure a composite representing the average. Sampling was conducted during the spring seasons of 1949, 1950, 1954, and 1955 when erosion of soil by wind was prevalent. The samples were collected from central and western Kansas and eastern Colorado. A total of 44 wind-eroded fields having a soil class ranging from sand to clay were included in the study.



547

Determinations of the physical and chemical soil characteristics included (a) the size distribution of dry particles and aggregates by the method of Chepil (1952), (b) the bulk density of dry particles by the elutriation method of Chepil (1950), (c) the size distribution of water-stable particles and aggregates by the modified method of Yoder (1936), (d) the mechanical composition by the method of Bouyoucos (1951), and (e) the organic matter by the method of Walkley (1947).

For the sake of simplicity only average values for each soil class are included in this paper.

THE NATURE OF ELUTRIATION

The size distribution of dry particles and aggregates in soil material of wind-eroded fields and of soil drifts originating from and trapped in the vicinity of the fields is shown in figure 1. Because the proportions of the finest grades in soil materials from wind-eroded fields and from the drifts was low but important compared with the proportion of the predominant grades, it was decided to follow the method of Bagnold (1943) for a graphic representation of the size distribution of these materials. This is done by plotting the logarithm of the percentage weight of soil, $\Delta p$, per unit of log-diameter scale against the logarithm of grain diameter. Assuming the diameter limits of each grade as determined by sieving to be $d_1$ and $d_2$, the logarithmic interval of grain diameter is given by log $d_1/d_2$ which, for convenience, is designated by $\Delta D$. The percentage weight of each grade per unit of log-diameter scale is then equal to $\Delta p/\Delta D$.

The soil material of wind-eroded fields (shown by hatched lines in figure 1) had either two or three diameter peaks, depending on soil class. The sand, loamy sand, and silty clay and clay had two peaks, one centered around 0.3 mm for sandy soils and around 0.6 mm for clayey soils and the other at about 25 mm for sandy soils and 10 mm for clayey soils. The intermediate-textured soils, on the other hand, had three distinct diameter peaks, one occurring at about 0.07 mm, another between 0.3 and 0.6 mm, and the third between 10 and 30 mm.

In soil material taken from the drifts (shown by continuous lines in figure 1) there was only one peak diameter. The peak was at either 0.4 or 0.6 mm depending on soil class. The peak diameter of the drifted material derived from fields composed of sand and loamy sand was about 0.4 mm and of drifted material from the finer-textured soils the peak was about 0.6 mm. The reason for the difference in the peak diameter was quite apparent. The drifted materials derived from fields of sand and loamy sand were composed principally of discrete, non-porous grains having an average bulk density of 2.37. The materials drifted from the finer-textured soils, on the other hand, were predominantly aggregates exhibiting a distinct degree of porosity and having an average bulk density of 1.70 (table 1). Their equivalent peak diameter, therefore, was equal to $\sigma d/2.65$ in which $\sigma$ is the bulk density of a discrete soil grain or aggregate of diameter d. In accordance with the above expression, the average equivalent peak diameter of grains eroded from these soil classes was also about 0.4 mm. The occurrence of a similar equivalent

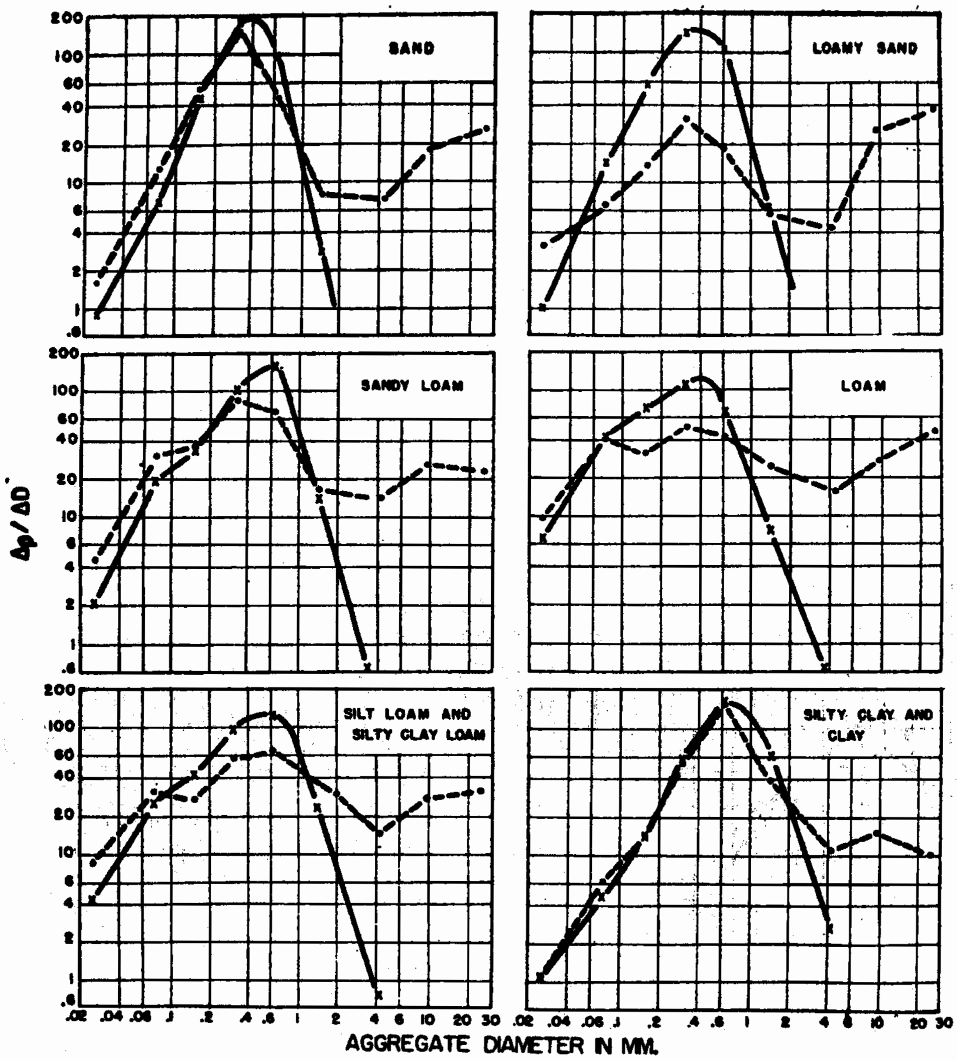


Fig. 1. Size distribution of dry aggregates in surface inch of soil material from wind-eroded fields (shown by hatched lines) and from soil drifts originating from and trapped in the vicinity of the fields (shown by continuous lines) for 6 textural groups of soils. The number of fields represented in the 6 textural groups, starting with the coarsest group, was 2, 3, 8, 12, 14, and 3.

peak diameter of erodible particles in all soil classes herein investigated is to be expected since the natural wind forces operating on all soils of the region were about the same.

The diameter peak centering about 0.07 mm in soil material of wind-eroded fields apparently caused a slight bulge in drifted material of the same diameter. The second peak in the soil material of wind-eroded fields coincided approximately with the peak diameter of the drifted materials. In no case, however, was the third peak in soil materials of the wind-eroded fields reflected in the composition of the drifted materials. The reason for this is clear. The size indicated by the third peak was definitely non-erodible and therefore did not influence the composition of the drifted materials. It is evident from figure 1 that some sizes on the extreme right side of the peak diameter of drifted materials were not moved by wind. The next smaller sizes exhibited some

TABLE 1
Average Bulk Density of Discrete Particles in Various Dry Sieve Fractions of Various Soils

| Soil | Particle bulk density in sieve grade | | | | | |
|---|---|---|---|---|---|---|
| | 2.0-.84 mm | .84-.42 mm | .42-.21 mm | .21-.1 mm | .1-.05 mm | <0.05 mm |
| Sand | 2.59 | 2.56 | 2.57 | 2.53 | 2.51 | 2.49 |
| Loamy sand | 2.09 | 2.11 | 2.31 | 2.40 | 2.16 | 2.11 |
| Sandy loam | 1.57 | 1.61 | 1.59 | 1.63 | 1.79 | 1.97 |
| Loam | 1.52 | 1.56 | 1.69 | 1.69 | 1.72 | 2.02 |
| Silt loam and silty clay loam | 1.57 | 1.57 | 1.63 | 1.64 | 1.78 | 1.82 |
| Silty clay and clay | 1.61 | 1.66 | 1.71 | 1.70 | 1.79 | 2.02 |
| Grand average | 1.82 | 1.84 | 1.92 | 1.93 | 1.96 | 2.07 |

movement, but their movement was apparently slow and low in magnitude. These fractions constituted the bulk of the lag materials moved primarily by surface creep. The next smaller fractions were centered around the peak diameter of materials found in drifts or dunes. They constituted grains moving primarily in saltation. Particles still smaller than these, shown on the left of the peak diameter, contained what may be termed the "dust" fraction. The dust particles moved rapidly, and a large proportion of them, especially on the extreme left of the peak diameter, were lifted in the air and carried away in what may be considered true suspension. However, there was no clear-cut demarcation where one soil grade ended and the other began. Transition from one grade to another was gradual and, in fact, one grade merged considerably with the other. One reason for this sort of overlapping was that some particles in surface creep moved intermittently in saltation and some of those in saltation no doubt were lifted by gusts of wind and carried in suspension. Even for a given type of movement the rate of movement of the individual soil particles was highly variable due to variation in size, shape, and density of the particles and to variation in the force of the wind.

An example of size distribution of particles in drifts and lag materials formed by unusually strong winds is given in figure 2. The peak diameter of particles in the lag materials was about twice as large as in the drifts. Same as particles in drifts, the lag materials were characterized by a single peak diameter with arms to the left and the right of the peak falling off independently at a more or less uniform rate.

### MAGNITUDE OF SORTING OF ERODED MATERIALS

Let it be assumed that a and b are the percentages of the sieve fraction in drifted material and in field soil, respectively, which have a grain diameter corresponding approximately to the peak diameter of the drifted material (fig. 1 and table 2). If the proportion of the next smaller sieve fraction c to fraction a in the drifted material is $\frac{c}{a}$ and the proportion of the same respective sieve fractions in the field soil is $\frac{d}{b}$, the percentage loss of fraction

TABLE 2

Average Size Distribution of Dry Particles and Aggregates of Surface Inch of Soil Material from Wind-eroded Fields and from Soil Drifts Originating from and Trapped in the Vicinity of the Fields

| | Dry sieve fractions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Source | >12.7 mm | 12.7-6.4 mm | 6.4-2.0 mm | 2.0-.84 mm | .84-.42 mm | .42-.21 mm | .21-.1 mm | .1-0.05 mm | <0.05 mm |
| | % | % | % | % | % | % | % | % | % |
| Fields | 8.7 | 6.7 | 6.1 | 8.4 | 21.9 | 25.2 | 11.0 | 7.2 | 4.8 |
| Drifts | 0 | 0.1 | 0.4 | 7.2 | 35.8 | 34.2 | 14.0 | 5.7 | 2.6 |

c from the drifted material is $100\left(\frac{d}{b}-\frac{c}{a}\right)/\frac{d}{b}$. Similarly, losses from the drifted soil of other sieve fractions on each side of the peak diameter can be determined. Losses of sieve fractions smaller than the peak diameter indicate the approximate proportions of various sizes of dust particles lost to the atmosphere, and losses of sieve fractions larger than the peak diameter indicate the approximate proportions of lag and non-erodible fractions which remained

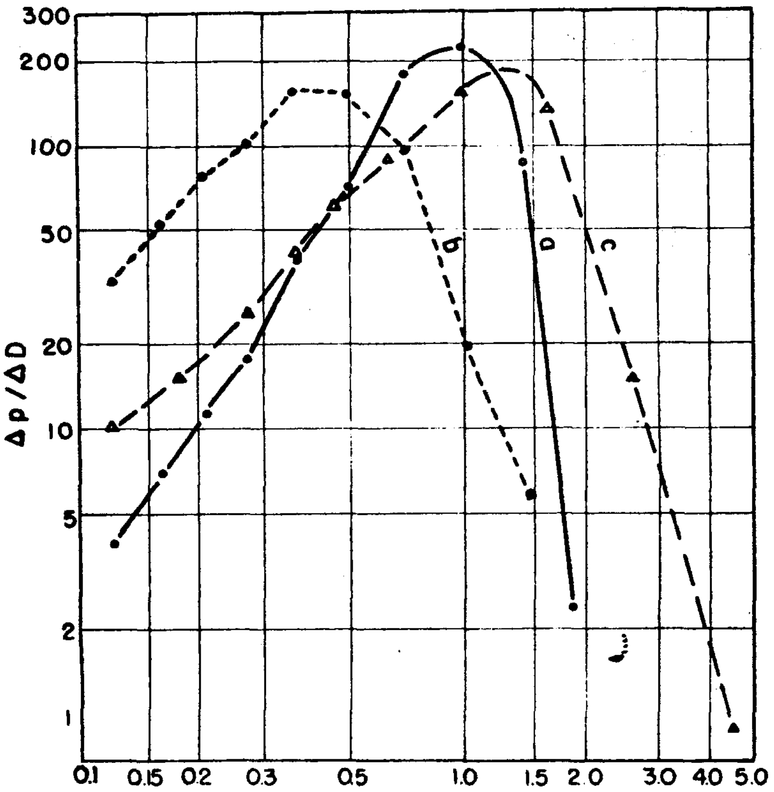


Fig. 2. Size distribution of soil grains moved by unusually high winds: (a) Lag material of average grain bulk density of 1.80 deposited in a 2-foot depression by a wind of 50 mph at a 5-foot height on March 24, 1949, near Salina, Kansas. (b) Material jumped across the depression and piled in drifts against a highway. (c) Lag material of average grain bulk density of 1.83 deposited in small gravel ridges by a wind of about 70 mph at a 5-foot height on February 19, 1954, near Tribune, Kansas.

in the field and from among which the highly mobile fractions were removed. Since the drifted materials accumulated usually in small dunes or drifts throughout the eroded area, they contributed appreciably to the general soil composition of the area. The dust raised in suspension, on the other hand, was carried far and wide and constituted that portion of the soil material lost from the wind-eroded region. The removal of dust by suspension is known as deflation.

In accordance with the above method of estimation, the approximate proportions by weight of dry dust particles lost from the various erodible sieve grades by the process of deflation are shown in table 3. These data show that the smallest soil particles deflated the most, whereas the particles approaching the peak diameter of the drifted material deflated least. Depending on soil class, from 32 to 84 percent of particles smaller than 0.05 mm in diameter and from 30 to 72 percent of particles between 0.05 and 0.1 mm contained in the wind-transported soil fraction were deflated by a single windstorm. The degree of deflation, i.e., the percentage of total quantity of dust deflated by wind, was least from silty clay and clay soils (table 3). Moreover, these soils contained the lowest proportion of the dust fraction (table 2). Consequently the magnitude of deflation (based on degree of deflation multiplied by the proportion of dust contained in the wind-eroded material) was least on silty clay and clay. On the other hand, the intermediate-textured soils, i.e., loam, silt loam, and silty clay loam indicated a high degree of deflation, contained the greatest proportion of dust subject to deflation, and therefore had the greatest magnitude of deflation.

TABLE 3
Average Proportion of Wind-eroded Soil Lost from Various Sieve Grades by the Process of Deflation

| Soil class of eroded fields | Proportion removed from sieve grades | | | | |
|---|---|---|---|---|---|
| | 0.84-0.42 mm | 0.42-0.21 mm | 0.21-0.1 mm | 0.1-0.05 mm | <0.05 mm |
| | % | % | % | % | % |
| Sand | 0 | 0 | 23 | 50 | 50 |
| Loamy sand | 0 | 0 | 12 | 55 | 78 |
| Sandy loam | 0 | 47 | 56 | 72 | 84 |
| Loam | 0 | 0 | 3 | 53 | 69 |
| Silt loam and silty clay loam | 0 | 6 | 14 | 56 | 74 |
| Silty clay and clay | 0 | 1 | 7 | 30 | 32 |
| Grand average | 0 | 9 | 19 | 53 | 64 |

## EFFECTS OF SORTING ON SOIL COMPOSITION

In virtually all soil classes investigated, the drifted materials contained much less fine and more coarse water-stable particles than the field soil (fig. 3). Apparently a considerable proportion of the fine water-stable particles in that portion of the soil moved by wind was removed by deflation. The coarse

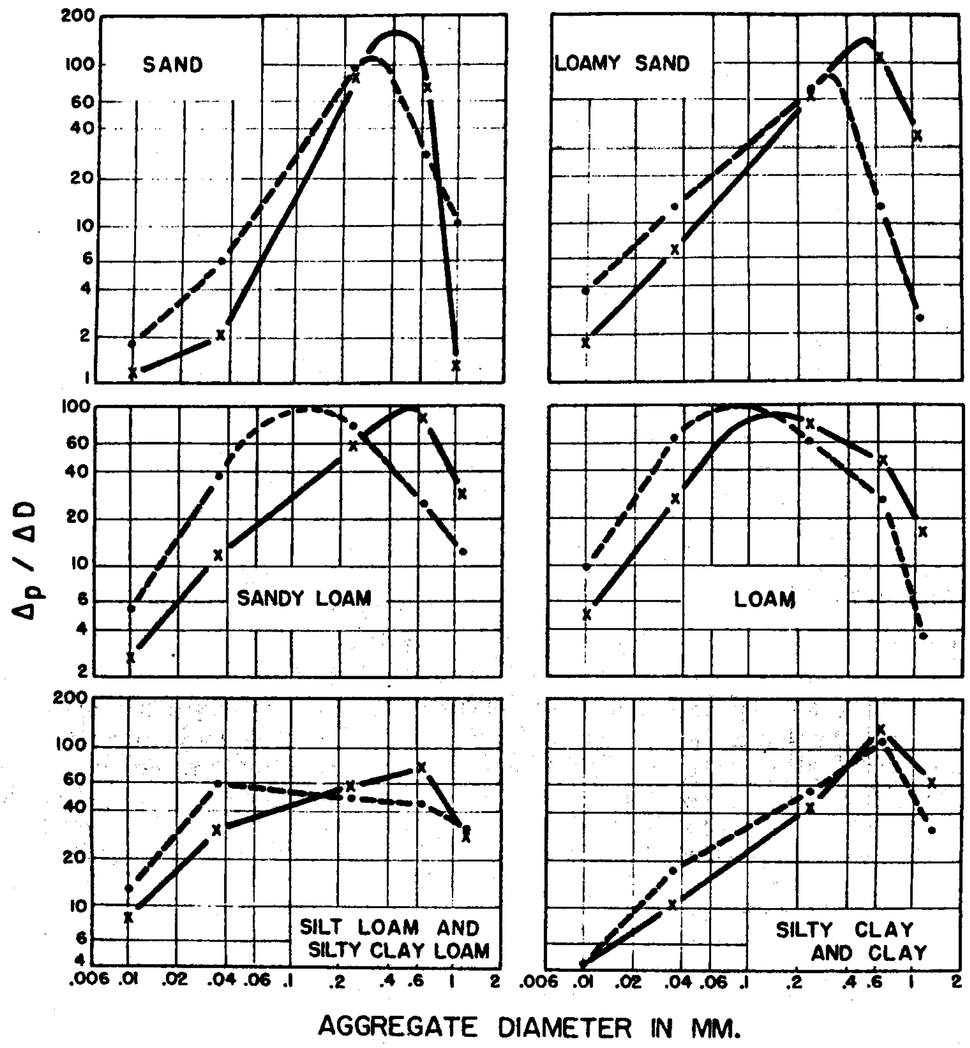


Fig. 3. Size distribution of water-stable aggregates in surface inch of soil material from wind-eroded fields (shown by hatched lines) and from soil drifts originating from and trapped in the vicinity of the fields (shown by continuous lines) for various textural groups of soil.

water-stable particles or aggregates, on the other hand, tended to accumulate in the drifts. Unlike the secondary dry aggregates or clods, the water-stable particles or aggregates appeared to be extremely resistant to disintegrating forces of wind erosion. Unfortunately, virtually all of them in each of the soil classes investigated were too small to resist movement by wind. There were apparently two distinct phases of the sorting of water-stable particles by the wind: (a) the removal from the drifted portion of one-third to two-thirds of the particles smaller than about 0.1 mm in diameter, and (b) accumulation into drifts of almost all of the remaining water-stable fractions.

The proportion of elementary mechanical fractions, sand, silt, and clay, was influenced considerably by the sorting action of wind erosion (table 4). The nature of the sorting action was not uniform in all soils; it varied appreciably with soil class. But there were some aspects of the sorting action that were present in all soils. In virtually all cases, for example, the proportion of sand increased, and in all cases the proportion of silt decreased in that portion of the soil that was moved and deposited in drifts by the wind. In the drifted materials, the original content of silt was reduced from 7 to 67 percent, depending on soil class. These reductions were statistically significant in all soil classes except sand, loamy sand, and clay. Lack of significant differences in at least some of these cases was apparently due to the fact that not more than two or three fields were chosen in each case.

The relative proportions of clay in the drifts and in the wind-eroded fields varied depending on soil class. All sandy soils had substantially lower proportions of clay in the drifts than in the fields, but all of the finer-textured soils had a somewhat higher proportion of clay in the drifted materials than in the field soils. In these latter soils the clay fraction apparently tended to stick to those particles or aggregates that were large enough to remain in the drifts in the vicinity of the eroded area.

The remarkable changes in mechanical composition of the soil fraction that was moved by wind were a result of a single windstorm! In virtually all sandy soils a storm was sufficient to change the texture of the wind-transported soil material from a loam to a sandy loam, or a sandy loam to a loamy sand, or a loamy sand to a sand. In finer-textured soils, on the other hand, such as in loessal soils, the sorting was far less pronounced. From these soils literally all of the three mechanical constituents moved by wind were lost substantially to the atmosphere, although the clay fraction appeared to be somewhat less mobile than the other two. Mobility here is interpreted not as the speed of

TABLE 4

Mechanical Composition and Organic Matter of Surface Inch of Soil Material from Wind-eroded Fields and from Soil Drifts Originating from and Trapped in the Vicinity of the Fields

| | | Mechanical composition | | | |
|---|---|---|---|---|---|
| Soil class | Source | Sand >0.05 mm | Silt 0.05-0.002 mm | Clay <0.002 mm | Organic matter |
| Sand | | % | % | % | % |
| | Fields | 91.8 | 3.3 | 4.9 | 0.44 |
| | Drifts | 97.2 | 1.8 | 1.0 | 0.30 |
| Loamy sand | Fields | 80.5 | 11.3 | 8.2 | 0.63 |
| | Drifts | 90.8* | 6.2 | 3.0 | 0.44 |
| Sandy loam | Fields | 64.8 | 23.0 | 12.2 | 1.19 |
| | Drifts | 84.9** | 7.7** | 7.4* | 0.62* |
| Loam | Fields | 36.8 | 45.6 | 17.6 | 1.78 |
| | Drifts | 50.2** | 31.9** | 17.9 | 1.62 |
| Silt loam | Fields | 18.4 | 58.2 | 23.4 | 2.41 |
| | Drifts | 17.0 | 53.4* | 29.6** | 2.53 |
| Silty clay loam | Fields | 22.2 | 49.1 | 28.7 | 2.27 |
| | Drifts | 24.4 | 45.6* | 30.0 | 2.35 |
| Silty clay and clay | Fields | 11.8 | 35.1 | 53.1 | 2.41 |
| | Drifts | 13.3 | 31.3 | 55.4 | 2.76 |

* Difference significant at 5 percent level by "F" test.
** Difference significant at 1 percent level by "F" test.

the particles through the air, but as their relative rate of removal from the soil.

One other soil element affected by the sorting action of the wind was the organic matter (table 4). Again, the effects of the sorting action varied, depending on soil class. In all sandy soils and in loam the organic matter content of the accumulated soil drifts was substantially lower than in the residual soil of the windblown fields. Much of the organic matter apparently was not bonded with the coarse soil fractions and was deflated readily by the wind. In loessal and fine alluvial soils the organic matter content of the accumulated soil drifts was somewhat higher than in the field soils. The organic matter in these soils apparently tended to be associated with that mineral portion of the soil that was not deflated by the wind. In addition, there was some accumulation of finely divided vegetative residue in the drifts. This was not so in sandy soils. Here the drifts as well as the residual soil of the windblown fields contained much less organic matter than the soil in non-eroded fields. Much of the organic matter in these soils apparently was carried into the atmosphere and was thus completely removed from the wind-eroded areas.

## CONCLUSIONS

The wind erosion process was composed of two major phases: the sorting of various primary and secondary soil fractions and the disintegration of the secondary fractions to the primary particles by the abrasive action of wind-eroded grains.

In the first phase, the wind-eroded soil material tended to be sorted out into several distinct grades some of which were as follows: (1) the non-erodible fractions remaining in their original locations in the field, (2) the so-called "lag" materials moving slowly by surface creep and deposited primarily in surface depressions throughout the field, (3) the grains moving rapidly in saltation and deposited usually in drifts or mounds throughout the affected area, and (4) the dust particles kicked up by the saltating grains to form dust clouds usually carried great distances from their source. The data indicated that removal of dust particles by deflation, although variable in magnitude, was appreciable for each soil investigated. On the average, almost 60 percent of the total dust content (particles smaller than 0.1 mm) in that portion of the soil moved by a single windstorm was deflated.

In the second phase of the wind erosion process, both the transported and the stationary soil fractions were disintegrated to smaller fractions by the abrasive action of the transported grains. The impacts of grains in saltation appeared to cause the greatest degree of abrasion. The secondary aggregates or clods tended to break down usually into primary (water-stable) aggregates most of which were readily transported by the wind. These primary aggregates in turn tended to break down into individual mechanical fractions—sand, silt, and clay.

Silt was more readily deflated than either sand or clay, except from soil classes such as sand and loamy sand already having a relatively low ratio of silt to clay. The silt particles exhibited little cohesion and were therefore readily separated by disintegrating forces of wind erosion (Chepil, 1955).

Moreover they were small enough to be readily deflated by the wind. The clay particles, on the other hand, exhibited great cohesive property and showed a definite tendency to form stable aggregates too large to be lifted into the atmosphere.

The sorting process of wind erosion has caused a profound change in the mechanical composition of some soils and little change in others, depending on their physical characteristics. On fine alluvial and loessal soils composed mainly of silt and some fine sand and clay, the sorting process of wind erosion did not appreciably change the elementary mechanical composition of the residual soils. Here the wind had no great tendency to sort out the various mechanical constituents. The sorting action was limited particularly to separation of the different sizes of the secondary particles or aggregates which apparently contained a more or less uniform proportion of each of the mechanical constituents.

In contrast, a considerable degree of sorting of elementary mechanical fractions occurred in loam and sandy soils. These soil classes contained a considerable proportion of sand too coarse to be deflated by the wind. Consequently, this sand fraction tended to remain in the drifts while much of the silt and clay was lost to the atmosphere. The drifts were deposited here and there within the affected area and added that much more to the general sandiness of the area. In addition to the reduction of organic matter and consequently of soil productivity, the depletion of silt and clay and the accumulation of sand added further to the hazard of wind erosion and to the problem of how to hold the remaining soil. The sorting of mechanical fractions such as occurred on these soils constitutes one of the most serious aspects of the wind erosion problem.

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