FUNCTION AND SIGNIFICANCE OF WIND IN SEDIMENTOLOGY[1/]

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1/ Contribution from the Soil and Water Conservation Research Division, Agricultural Research Service, USDA, and the Kansas Agricultural Experiment Station. Department of Agronomy Contribution No. 809.

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ABSTRACT

The actions of wind on soil may be classed roughly into three categories: (1) Soil removal, (2) deposition, and (3) mixing. The wind's activity on soil is mostly in arid regions, but deposition extends even onto the humid regions.

Erosion of soil by wind includes three types of soil movement — saltation, surface creep, and suspension. Impacts of grains in saltation cause movements by surface creep and suspension. Dust carried in suspension is lifted by upward currents of turbulent wind. Once lifted off the ground, it is carried high in the air and is deposited in uniform layers far from its source. Fine dust may circle the earth many times. The composition of freshly deposited dust is like the composition of loess of the Pleistocene age. Estimates show that during the last 40 years an equivalent of 1.2 inches of soil material, on the average, has been removed from the Great Plains of about 750,000 square miles. Some areas had as much as 9 inches removed in 20 years.

Removal of dust from one source is compensated by deposition elsewhere. Estimates have shown that during the last 20 years about one-half inch of atmospheric dust has been deposited in grassland near the wind-eroded region. Research is being undertaken to determine rates of deposition in humid regions of the United States.

Introduction

Unlike water, which tends to carry the soil from higher to lower elevations onto alluvial plains and into the sea, the wind scatters the fine soil constituents and deposits them in a uniform mantle over extensive areas near and far from their source. Removal of these fine soil materials from one area is therefore somewhat compensated by deposition at another. Movement also occurs in reverse so that considerable mixing of soils great distances apart occurs.

Removal is mostly from arid regions, but deposition and mixing extends imperceptibly to a casual observer even onto the humid regions. With respect to deposition and mixing, the wind may be considered a soil forming factor, but with respect to accelerated removal, it is one of the great destructive agents of soils.

Nature of Wind Erosion

Wind erosion is characterized by three types of soil movement — jumping (saltation), rolling and sliding (surface creep), and floating in the air (suspension). Impacts of grains in saltation cause movements by surface creep and suspension (Chepil and Woodruff, 1963).

Saltation is caused by lift and drag forces against the surface. The saltating particles are the most erodible. They range from about 0.1 to 0.5 mm. in equivalent diameter (based on 2.65 density).

Particles too large to be moved by wind alone creep readily under impacts of saltation. They range from about 0.5 to 2 mm. in equivalent diameter, depending on wind velocity.

Contrary to general opinion, dust is highly resistant to erosion by direct pressure of the wind but is readily moved by impacts of larger particles moved in saltation. Once kicked up by saltation, it is carried by the upward currents of turbulent flow. Dust carried in suspension is generally less than 0.1 mm. in equivalent diameter. Dust clouds often rise 3,000 to 4,000 meters and are the most visible and therefore the most dramatic aspects of dust storms (figure 1).

Abrasion

The impacts of saltation also cause clods and surface crust to disintegrate to small fragments, which in turn are moved by wind. The longer erosion continues and the more the wind shifts from different directions, the greater is the quantity of erodible material formed by abrasion and the higher the rate of erosion. The materials detached from clods and surface crust tend to accumulate in dunes or drifts toward the leeward side of fields and, if they are fine, to be carried far through the atmosphere. The smaller the detached dust particles, the farther they are transported by the wind (Chepil and Woodruff, 1963).

Avalanching

The tendency for saltating grains to accumulate toward the lee of fields causes an increase of erosion (avalanching) for a distance of 500 yards or more before the maximum soil flow that a wind of a given velocity can sustain is reached. Often the maximum flow is not reached because the distance across the eroding field is limited. The rate of soil avalanching varies directly with soil erodibility, that is, the more erodible the soil, the greater is the rate of avalanching and the shorter the distance at which maximum rate of erosion (soil flow) is reached. By the same token, the more erodible the soil, the narrower the erodible field has to be to keep the rate of soil flow down to a tolerable limit. This limit is generally taken as 0.2-ton-per-rod-width-per-hour under a 40-mile-per-hour wind velocity for bare soil before cultivation in spring. This is one-tenth of the possible maximum intensity that would occur under the same conditions without restricted distance across an erodible field (Chepil, 1957a).

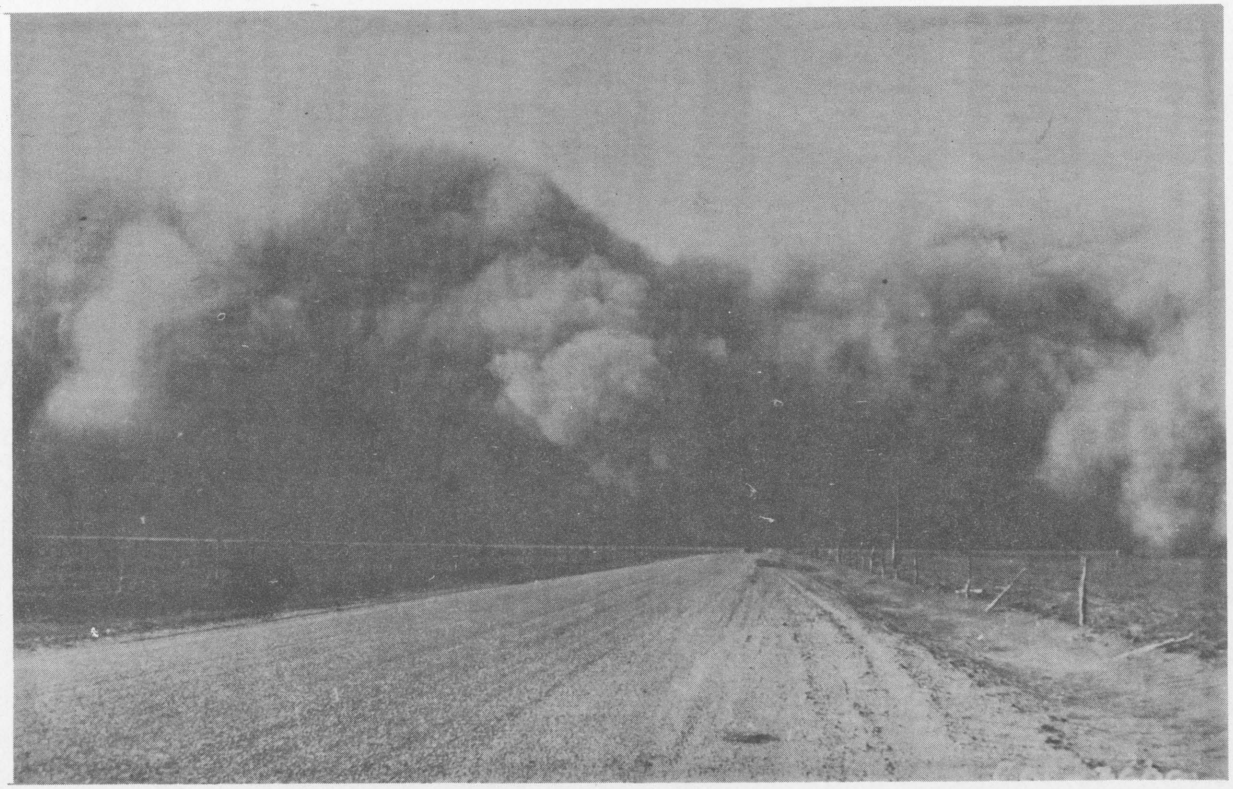

Figure 1.--Great quantities of dust are moved long distances during periods of wind erosion. Black blizzards such as this are the most dramatic aspects of dust storms. (Soil Conservation Service photo.)

Sorting

The wind acts on many soils like a fanning mill on grain — removing the finer fractions and leaving the coarser ones behind (Daniel, 1936; Chepil, 1957b). Silt and clay are thus removed and lag sands and gravels are left behind. This sorting action acting on the soils for many years makes them progressively coarser in texture. Finally, nothing is left but the infertile, skeletal material forming shifting sand dunes and gravelly pavements. History of many old civilizations is a record of struggles against such deterioration of the land (Jacks and Whyte, 1939; Bennett, 1939).

Sorting occurs on soils developed from glacial till, residual material, mountain outwash, and sandy materials of various origins. The wind separates such materials into several distinct grades:

Residual soil materials: Nonerodible clods and rocks that remain in place.

Lag sands, lag gravels, and lag soil aggregates: Semierodible grains that are moved slowly by wind and deposited here and there on the surface of eroded areas. They are moved primarily as surface creep.

Sand and clay dunes: Highly erodible grains usually not very far removed from an eroded area. Their movement is primarily in saltation.

Loess: Dust which once lifted off the ground by impacts of saltating grains is carried high in the air and is deposited in uniform layers near and far beyond the dunes. Dust is carried in true suspension. The composition of freshly deposited dust is like the composition of the loess deposited in the Pleistocene age (Swineford and Frye, 1945; Péwé, 1951; Warn and Cox, 1951; Chepil, 1957b). Huge deposits of loess in many parts of the world show the great importance of wind as a geologic mover of dust.

In some cases, wind erosion almost completely removes the surface soil. This nonselective removal by wind is associated with loess which was already sorted and deposited from the atmosphere during past geologic eras.

Soil Removal

In the southern High Plains of the United States, Daniel (1936) studied the physical changes in soils under cultivation and accelerated wind erosion. His studies were based on a comparative difference in mechanical composition of virgin soils and drifted material from cultivated land. He found that soil materials carried by wind from coarse and medium textured soils and subsequently deposited in drifts contained on the average 38 percent less silt and clay and 29 percent more sand than the adjacent virgin soil. No direct comparison was made of the composition of virgin and adjacent cultivated soil.

In Canada, Doughty et al. (1949) studied the physical and chemical changes in soils brought about by cultivation and erosion in the brown, chestnut, and black soil zones on the Prairie region. Their study was based on direct comparison in physical and chemical composition between cultivated and adjacent virgin soils. They found that:

(a) The greatest loss of silt, clay, and organic matter due to cultivation occurred on extremely sandy soils and the least on clay soils.

(b) Many loamy sands lost virtually all silt and clay that they contained under virgin conditions less than 60 years previously. During dry periods, some of these soils changed to shifting dune sand and were abandoned. During wet periods, vegetation encroached and stabilized some of the active dunes.

(c) Sandy loams lost about 15 percent of their original silt and clay content in the top 4 inches of soil and gained a corresponding proportion of sand. Provided the same rate of selective removal continues in the future, these soils will turn to virtual sand dunes within 150 or fewer years of cultivation.

(d) The medium-textured glacial till loams and silt loams lost on the average 6.5 percent of their original silt and clay in the 4 inches of top soil. At this rate of loss, about 500 to 1,000 years would be required for the surface soil material to change to dune sand.

Further studies of mechanical sorting of soil by wind in Kansas and Colorado (Chepil, 1957b) showed that on loess soils, i.e., soils derived from material originally deposited by wind during the Pleistocene period, wind erosion did not affect the texture of the drifts or the residual soil. But on soils derived from Permian sandstone, the drifts contained 65 percent more sand and 65 percent less silt and clay than the residual soil. The wind-eroded fields contained 17 percent more sand than the adjacent noneroded fields. Depth of sampling in all cases was 1 inch. This change in condition of the soil was a result of only two or three windstorms that occurred in 1 week when 0.85-inch depth of soil was removed from the eroded fields.

Daniel (1936) and Chepil (1957b) found that removal of soil by wind with or without any sorting caused the general depletion of organic matter by virtue of some or all of the top soil, in which organic matter is generally concentrated, being removed. Where sorting of soil material occurred, the damage to surface soil (to depth of cultivation) was two-fold: (a) Depletion of organic matter, and (b) removal of silt and clay. The drift soil (soil that has been moved about by the wind and deposited in drifts on or near eroded fields) contained 71 percent sand compared with 38 percent in the top 4 inches of noneroded fields. This depletion of silt and clay added further to the hazard of wind erosion and to the problem of how to hold the remaining soil.

Another study on the effects of wind erosion was conducted in western Kansas in 1949 and 1950 on soils developed from loess (Chepil et al., 1952). These soils belong to the Ulysses and Baca series. Some parts of this region had approximately 60 percent of the land in native sod before World War II. Progressive breaking of the sod for cultivated crops started in 1942 and was virtually completed in 1950. A unique opportunity, therefore, existed to determine possible changes in soils associated with time-after-breaking. Physical and chemical analyses were conducted on (a) 31 newly broken fields (broken between 1936 and 1948), (b) 31 intermediate (broken between 1939 and 1944), and (c) 30 old cultivated (broken before 1936). The study showed that:

(a) The old cultivated fields had little or no topsoil (A horizon) left. The average distance to the lime layer was 10 inches, whereas on newly broken land it was 19 inches. This means that 9 inches of soil were gone within an agricultural history of about 2 decades.

(b) There was no appreciable accumulation of drifted material. Much of it was apparently fine enough to be carried into the atmosphere the same way it arrived. Only slight quantities of sandy material were observed near an occasional temporary watercourse.

(c) On the old cultivated fields the B horizon constituted the surface soil. This soil contained more clay and less silt and sand than the surface soil of the newly broken land (table 1).

(d) There was substantially less organic residue (stubble and straw) in old than in newly broken fields. Apparently, the productivity of the old cultivated fields had dropped considerably during the short period under cultivation. This resulted in greater exposure of the soil to wind and water erosion. However, the soil of the old cultivated fields was cloddier and contained more coarse (> 0.5 mm.) water-stable aggregates than did the newly broken fields.

(e) Soil losses, as measured by wind tunnel tests (table 1), were smaller from old cultivated fields than from newly broken fields, despite the newly broken fields having more crop residues. It is evident that the greatest rate of removal of soil by wind would occur within a few dry years after breaking. The native grasses were effective in creating a loose, finely granulated soil structure — a structure highly susceptible to erosion by wind. However, the grasses were able to protect the soil from erosion. Accelerated erosion occurred only after the land had been denuded of vegetation by overburning, overpasturing, and overcultivation (Malin, 1946).

TABLE 1.--Physical and chemical properties of surface soils at various periods after breaking of virgin sod in western Kansas.

Number of fields	Years after breaking	Clay < 0.002 mm.	Total organic matter	Nitrogen	Organic residue > 1.19 mm.	Clods > 0.84 mm.	Water-stable aggregates > 0.5 mm.	Amount eroded in wind tunnel	Computed erodibility*
	average	%	%	%	%	%	%	tons/acre	tons/acre
30	19	21.0	2.13	0.120	0.67	58.1	12.9	0.40	0.49
31	6	18.0	2.49	0.129	0.89	54.4	11.6	0.46	0.60
31	2 1/2	17.0	2.53	0.129	1.13	50.2	10.3	0.64	0.80
Level of significance		Differences necessary for significance at indicated levels							
1%		2.3	0.37	0.013	0.24	4.5	2.4	0.25	0.25
5%		1.7	0.28	0.010	0.21	3.3	1.8	0.19	0.18

* Based on dry soil fractions > 0.84 mm. Data from Chepil, Englehorn, and Zingg (1952).

To trace the removal of soil beyond the eroded fields, Chepil and Woodruff (1957) measured dust concentration in the air during dust storms. They found that the average rate of dust movement in western Kansas and eastern Colorado during the 1954 and 1955 dust storms was about 10,000 tons per hour per vertical square mile against the earth's surface.

Further analyses of the Chepil and Woodruff (1957) data indicated that the total duration of the 1954 and 1955 dust storms at Dodge City, Kansas, (which lies on the eastern outskirts of the severely wind-eroded area) was about 435 hours. This means that 4.35 million tons of dust per square mile perpendicular to wind direction moved past that location and presumably from the wind-eroded area during 1954 and 1955. Assuming that this region is 400 miles wide along the direction of wind and that an acre-foot of soil weighs 2,000 tons, 0.1-inch depth of soil emigrated during 1954 and 1955. From the 1922-1961 weather records at Dodge City, the total duration of dust storms was estimated to be 5,200 hours. Assuming that the intensity of dust storms was the same throughout the whole period, the net removal during the 40 years was 1.2 inches (3 cm.) of soil. This estimate would be greater or smaller if we assumed the region to be narrower or wider than 400 miles along the direction of wind and greater if the dust transported above 1 mile were considered. On this basis, it is estimated that 48 million acre-feet of soil were removed from the United States portion of the Great Plains of about 750,000 square miles during the 40 years. Some dust might have been brought into the wind-eroded region, but because the region is practically surrounded by mountains and humid regions, the immigrated quantity was probably relatively small.

Deposition and Mixing

The Great Plains region's loss must have been compensated by some other regions' gain. It is reasonable to expect that considerable dust deposition must have occurred in the more humid areas, especially east of the wind-eroded region. Preliminary measurements indicated that between 5 and 10 tons of dust per acre per annum were deposited at Manhattan, Kansas, (in the wet subhumid region) during 1954 and 1955. Smaller depositions probably occurred east of that location. No information is available on what these quantities might have been for areas farther east or west of the Great Plains. Such information would be exceedingly valuable in helping to determine rates of soil renewal in different regions.

Considerable information is available on the depth, composition, and distance from source of loess deposited in past geologic eras (Hanna and Bidwell, 1955; Waggoner and Bingham, 1961). Some information on the composition and source of dust presently deposited from the atmosphere in different regions is also available (Swineford and Frye, 1945; Warn and Cox, 1951; Péwé, 1951; Chepil, 1957b). Furthermore, Free (1911) estimated from meager data that the mean annual deposit east of the Mississippi River at that time was not less than 0.01 inch (1.67 tons per acre).

Authentic records of distance that dust can travel are rare. Free (1911) cited records which indicated that dust can travel thousands of miles from its source. One notable example is that of Australian dust storms reaching New Zealand, 1,500 miles distant. Another is that of dust originating in the Sahara and traveling over southern and central Europe to Germany and England, about 2,000 miles. During the 1930's, dust deposits presumed to have originated in the Great Plains were observed on the Atlantic seaboard 1,500 miles away. No information appears to be available in the literature on probable quantities of dust that could be trapped and retained with suitable land management. Therefore, in 1954, Chepil (unpublished data) had undertaken to find out rates of accumulation of aeolian material on sand and loamy sand in southwestern Kansas as influenced by land management. On land that had been returned to grass in 1946, a distinct layer of dust was present. The average depth of the dust layer was 0.4 inch (table 2) and its composition was a loam containing 64 percent silt and clay. Some of the dust evidently worked its way down about 1 inch deep, probably from insect and rodent activity and tramping by livestock. It is evident that the grass trapped at least one-half inch of aeolian material in approximately 10 years. The nearest cultivated field was about a mile away. On this field there was no evidence of dust accumulation (table 2). Here, the sandiest soil was the topmost one-half inch. The surface soil evidently had been losing the finer mechanical constituents as fast or faster than it had been gaining them.

It is evident from this study that a fine soil texture, comparable to that of loess, can be regained slowly under grass on sandy soils in dry regions such as western Kansas if wind erosion on surrounding cultivated lands continues at the rate it has in the recent past.

Conclusions

The greatest damage from wind erosion has been the removal of fine constituents from soils containing a certain proportion of sand. This sorting action is apparently responsible for the formation of sandy wastes in dry regions.

On loess soils there is no such sorting action; the whole soil is removed bodily by the wind. The degree of damage to soil here is governed primarily by the depth of available soil material.

The rate of soil removal since the breaking of virgin sod in dry regions has been enormous when considered in terms of the probable time required for soil material to be formed or laid down. Some of the stable grassland has been changed to shifting dunes within a generation.

The extensive damage from erosion in dryland regions has been due to lack of adjustment between methods of land use and environment. Extensive grain growing has been one of the primary factors contributing to erosion. Why? Because greater income can be derived from grain than from utilizing native grass. Agricultural use of the land, therefore, has been developed largely on the basis of immediate rather than permanent

TABLE 2.--Average composition and depth of atmospheric dust deposited in grass in western Kansas during 1946-1956.

Site description	Depth	Mechanical composition in 1956		
		Sand > 0.05 mm.	Silt 0.05-0.002 mm.	Clay < 0.002 mm.
	Inches	%	%	%
Good grass cover established on abandoned cultivated land in 1946	0-0.4	35.6	40.3	24.1
	0.4-0.9	70.0	22.2	7.8
	0.9-1.9	89.7	7.1	3.2
	1.9-3.9	82.8	11.7	5.5
	3.9-5.9	82.0	10.8	7.2
Land cultivated primarily to grain sorghum since 1935	0-0.5	85.1	10.6	4.4
	0.5-1.0	86.4	9.4	4.5
	1.0-2.0	82.4	11.2	6.4
	2.0-4.0	77.3	15.7	7.4
	4.0-6.0	77.8	14.8	7.4

returns from the land. This has resulted in considerable soil dissipation. Future population (if and when it expands beyond what the land will easily support) will pay for this dissipation.

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