Wind Erosion: Processes and Effect on Soil Productivity

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ABSTRACT

PART one concerns basics of the erosion process in terms of particle dynamics, threshold conditions, particle flux, and the protective role of nonerodible elements. Part two is a procedure for evaluating wind-erosion effects on soil loss and, subsequently, on crop yields. In the procedure, a wind-erosion equation is used to predict potential annual loss, which is converted to crop-yield reduction per centimeter of erosion for wheat, grain sorghum, and corn. Where applied in the Oklahoma Panhandle (in 2 1/4 counties), the procedure resulted in estimated annual yield reductions of wheat and grain sorghum equivalent to a total crop failure on about 4,530 ha (11,200 acre, or 17.5 sections) of the 163 300 ha (403,500 acre) of cultivated sandy surface soils in the selected area.

Wind erodes land every year in the United States, especially in the Great Plains and Far West and where there are coastal sands, organic soils, and interior sandy soils. The extent and degree of damage depends on soil, crop (cover), and climatic conditions existing at specific locations.

PART I: BASIC EROSION PROCESSES

The conditions under which wind erosion occurs have been well-documented (Bagnold, 1943; Chepil, 1945-46, 1953-55; Chepil and Woodruff, 1963; Woodruff et al., 1972). Erosion may be expected wherever the surface soil is finely divided, loose, and dry; the surface is smooth and bare; and the field is unsheltered, wide, and improperly oriented with respect to prevailing wind direction.

Particle Dynamics

Soil particles move in response to the dynamic forces generated by fluid flow. In air, a wind strong enough to move soil particles is always turbulent (Chepil and Woodruff, 1963). Few writers have attempted to describe exactly the initial motion of the first particles moved by fluid. Before 1962, most writers were satisfied by Bagnold's (1943) statement: "A critical windspeed was reached when the surface grains, previously at rest, began to be rolled along the surface by direct pressure of the wind. A foot or so downwind of the point at which rolling began, the grains could be seen to have gathered sufficient speed to start bouncing off the ground." Bisal and Nielsen (1962) concluded, after observing particles in a shallow pan mounted on the viewing stage of a binocular microscope, that the majority of erosive particles vibrated with increasing intensity as windspeed increased and then left the surface instantaneously (as if ejected). More recently, Lyles and Krauss (1971), from wind tunnel observations, reported that as mean windspeed approached the threshold value, some particles (0.59 to 0.84 mm in diameter) began to vibrate (rock back and forth) at an average frequency of 1.8 ± 0.3 Hz. That supported their hypothesis that the particle-vibration frequency is related to the frequency band containing the maximum energy of the turbulent motion (average value of the peak frequency of the longitudinal energy spectra was 2.3 ± 0.7 Hz).

More comprehensive research on particle vibration or oscillation is needed to (a) investigate the effects of particle size and density on vibration frequency, (b) determine the vibration-frequency increase before particles translate, (c) estimate the proportion of total particles that exhibit vibration, and (d) devise accurate methods of measuring vibration frequency.

When a particle is initially dislodged from the surface, it moves downwind by suspension, saltation, or surface creep. Particles transported in suspension, generally less than 100 μm in diameter (perhaps less than 50 μm would be more common), may be carried to high altitudes and over long distances, depending on their size, shape, and density (Malina, 1941). Saltating (jumping) particles, 100 to 500 μm, leave the surface but are too large to be suspended by the flow; on return to the surface they initiate movement of other particles. The bulk of total transport, roughly 50 to 80 percent, is by saltation. Most saltating particles rise less than 120 cm; the majority less than 30 cm. Particles moving in surface creep (500 to 1,000 μm), too large to leave the surface, are pushed and rolled (driven) by saltating particles. Reportedly, surface creep constitutes 7 to 25 percent of total transport (Bagnold, 1943; Horikawa and Shen, 1960).

Threshold Conditions

Bagnold (1943) used an experimental coefficient, A, to describe the threshold friction velocity, u_{*t}, (defined as $(\tau_0/\varrho)^{1/2}$, where τ_0 is the shear stress at the boundary and ϱ is air density). The equation is:

$$u_{*t} = A(\alpha g d)^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots [1]$$

where
α = immersed density ratio,

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$\frac{\rho_s - \rho}{\rho}$ = (ρ_s is particle density and ρ is fluid density);
g = gravitational constant; and
d = particle diameter.

In air, A has a value of 0.08 to 0.12 and perhaps as large as 0.2 in the absence of saltation flow. Iverson et al. (1973) and Wood et al. (1974) noted that A is a function of the particle-friction Reynolds number,

$$R = \frac{u_* d}{\gamma}$$

where γ is kinematic viscosity of the fluid. In Wood's summary of previous research, A ranged from 0.08 to 0.22 for R greater than 0.7; however, most values were between 0.08 and 0.12. Some question remains on what value to use for d in materials of wide-particle-size range. Also, no standard method of determining u_{*t} has been used or specified. Theoretically, $u_{*t} \equiv u_{*max}$ for $q \equiv 0$ (where q is particle flux), but it is difficult to measure experimentally.

Particle Flux

Several equations have been developed to predict the soil flux (mainly saltation and creep) from an area under specific soil and wind conditions. Most equations, empirically developed, relate the mass of soil moved to surface-shear stress or friction velocity of the wind and erodibility characteristics of the soil.

The functional form of those equations is:

$$q_s = f(d^a, \bar{u}_z^b \text{ or } u_*^c) \qquad [2]$$

where q_s is particle flux (mass per unit width per unit time); d, particle diameter; $\bar{u}_z$, mean windspeed at some reference height z; u_*, friction velocity; and a, b, c are constants. The mean velocity-profile parameter, u_* (often used to indicate the wind's capability to erode soil particles), is usually obtained from this equation:

$$u_* = \bar{u}_z \, k / \mathrm{Ln}\left(\frac{Z - D}{Z_o}\right) \qquad [3]$$

where
k = von Karman's constant (0.4);
D = effective roughness height;
Z_o = roughness parameter;

and other terms as previously defined. Equation [3] is applicable to adiabatic flows in the lower 10 to 20 percent of the boundary layer. Specific flux equations for *all erodible* particles are contained in reports by O'Brien and Rindlaub (1936), Bagnold (1943), Zingg (1953), Owen (1964), and Kadib (1965). The rates of discharge vary considerably among the equations because of different values found for the constants and for coefficients introduced in explicit equations.

An equation for transport of field soils is complicated by factors other than erodible-particle-size gradation—like proportion of fine-dust particles present, proportion and size of nonerodible fractions, field roughness, vegetation, and soil moisture content.

Gillette et al. (1972) developed a horizontal-soil-flux equation using parameters in the "wind erosion equation" (Woodruff and Siddoway, 1965). That equation is:

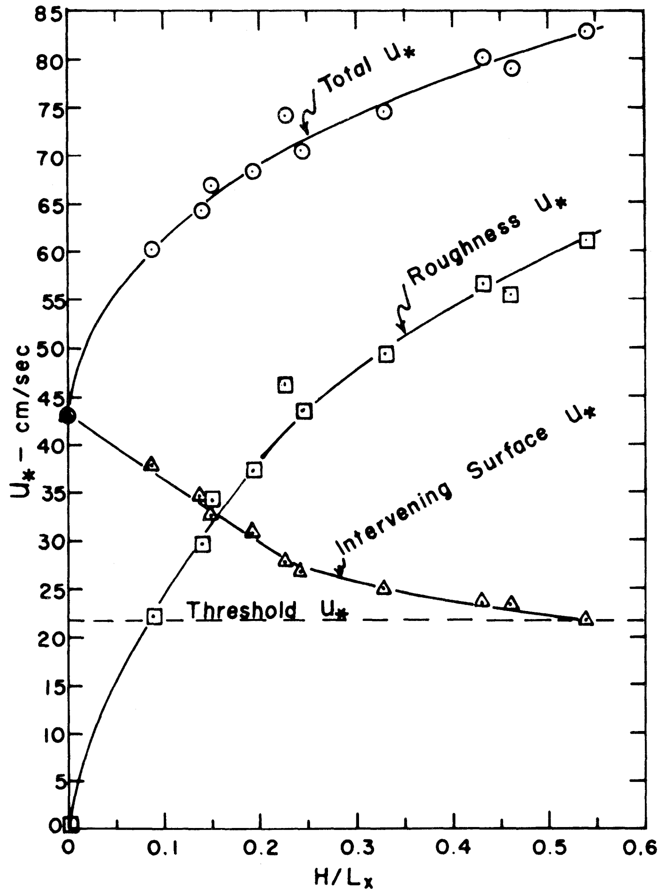

FIG. 1 How friction velocity (drag) changes as an erodible surface stabilizes by exposing nonerodible roughness elements (from Lyles et al., 1974). H/L_x is height of roughness element divided by the distance between nonerodible elements.

$$F = 2\,\frac{LX(\tau/\tau')^{3/2}}{16{,}500} \qquad [4]$$

where
F = horizontal soil flux in tons per rod width per hour;
L = field length in feet;
X = wind tunnel erodibility (Chepil and Woodruff, 1959);
τ = observed momentum flux; and
τ' = reference flux (Chepil, 1957) corrected for soil moisture (Chepil, 1956).

Predictions of wind erosion agreed qualitatively with observed vertical soil fluxes. However, further refinements in calculations expressing effects of soil moisture, wind velocity, roughness, and vegetative residues are necessary for good quantitative predictions in the field.

Nonerodible Elements

The protective role of nonerodible elements in the erosion process has been characterized by Lyles et al. (1974). In wind-tunnel studies they used all erodible sand particles and dowels as nonerodible elements to derive friction-velocity changes (Fig. 1). Initially, a soil with buried, nonerodible elements such as clods is eroded by a wind of characteristic friction velocity, u_*.

TABLE 1. EFFECT OF TOPSOIL THICKNESS ON CROP YIELDS. (DATA FROM LYLES, 1975)

Crop	Average yield reduction per cm of topsoil loss, kg/ha	Average yield reduction per cm of topsoil loss, percent
Wheat	39.7 ± 13.2	2.1 ± 0.8
Corn	96.4 ± 22.2	2.5 ± 0.5
Grain sorghum	59.3*	2.0*

*Not enough samples to compute valid standard deviation.

As erodible material is removed, the roughness is increased, which increases the friction velocity. The friction velocity may be thought of as being divided between the nonerodible elements (roughness, u_*) and the erodible soil (intervening-surface, u_*). Thus, as more erodible material is removed from the initially smooth, erodible surface, more drag is absorbed by nonerodible elements and less is absorbed by the erodible soil. After sufficient time, enough soil is eroded so that the intervening-surface, u_*, drops to the threshold level where erosion ceases and the soil is stabilized. Stabilizing agricultural fields by nonerodible elements is complicated by variation in speed, direction, and duration of winds plus possible generation of erodible-size particles from larger aggregates by abrasion. However, the role of nonerodible elements is clearly to absorb part of the total wind drag—reducing the drag on erodible particles.

Recently, Lyles and Allison (1976), from wind tunnel studies, published a regression equation that predicts the degree of protection provided by standind crop residues and nonerodible soil aggregates;

$$(u_*/u_{*t})s = 1.638 + 17.044 \frac{NA_s}{A_t} - 0.117 \frac{L_y}{L_x} + [(1.0236)^C - 1] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [5]$$

where $(u_*/u_{*t})_s$ is called the critical friction-velocity ratio (CFVR), because when this value is exceeded, erosion begins—the larger the ratio, the greater the wind erosion protection. The term u_* is the total friction velocity when a surface stabilizes at a given free-stream velocity, and u_{*t} is the threshold friction velocity for the erodible particles in question. The other parameters are: N/A_t, number of stalks in area A_t in cm^{-2}; A_s, average silhouette area (projected area facing flow) of a single stalk in cm^2; L_y distance (center-to-center) between stalks normal to wind direction in cm; L_x, distance (center-to-center) between stalks in the wind direction in cm; and C, percentage of dry soil aggregates greater than 1.0 mm in diameter. Research is needed to test equation [5] under field conditions.

PART II: WIND EROSION AND SOIL PRODUCTIVITY

Little attention has been given to quantifying the effects of wind erosion on intrinsic soil productivity. Loss of topsoil, plant nutrients, and organic matter, and changes in soil texture have been used to imply lower productivity (Chepil et al., 1962; Daniel, 1936; Daniel and Langham, 1936; Moss, 1935). Recently, Lyles (1975) suggested that effects of wind erosion on crop production might be determined by relating topsoil thickness or topsoil removal (excluding fertilizer effects) to crop yield (Table 1), then computing the potential average annual soil loss using a wind erosion equation (Woodruff and Siddoway, 1965). By converting annual soil loss to depth of soil removed, corresponding loss in crop yield could be estimated.

Various assumptions were made for the factors in the wind erosion equation:

$$E = f(I, K, C, L, V) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [6]$$

where
E = the potential annual soil-loss rate;
I = soil erodibility;
K = the soil ridge-roughness factor
C = climatic factor
L = the unsheltered distance across a field along the prevailing wind-erosion direction and
V = equivalent vegetative cover.

The equation was solved for E for different wind-erodibility groups (WEG, Table 2) and converted to depth-of-soil loss per year under two cropping systems that assume good residue management, i.e., stubble mulching (Table 3). Except for WEG 1-2 in West Texas, erosion is slight during the fallow year of a wheat-fallow rotation and the sorghum "year" of a wheat-sorghum-fallow (WSF) rotation. Soil losses were similar for the wheat and fallow "years" of a WSF rotation because

TABLE 2. DESCRIPTIONS OF WIND ERODIBILITY GROUPS (WEG)*

WEG	Predominant soil textural class	Dry soil aggregates > 0.84 mm, percent	Soil erodibility "I", MT/ha/yr
1	Very fine, fine, and medium sands; dune sands.	1	696
2	Loamy sands; loamy fine sands.	10	301
3	Very fine sandy loams; fine sandy loams; sandy loams.	25	193
4	Clays; silty clays; noncalcareous clay loams and silty clay loams with more than 35 percent clay content.	25	193
4L	Calcareous loams and silt loams; calcareous clay loams and silty clay loams with less than 35 percent clay content.	25	193
5	Noncalcareous loams and silty loams with less than 20 percent clay content; sandy clay loams; sandy clay.	40	126
6	Noncalcareous loams and silty loams with more than 20 percent clay content; noncalcareous clay loams with less than 35 percent clay content.	45	108
7	Silts; noncalcareous silty clay loams with less than 35 percent clay content.	50	85

*Data from Hayes, 1972.

TABLE 3. AVERAGE POTENTIAL SOIL LOSS FOR DIFFERENT WIND ERODIBILITY GROUPS AND CROP ROTATIONS AT SEVERAL LOCATIONS

Location	Wind erodibility groups (WEG)* 1	2	3-4L	5	6	7
	Wheat-fallow rotation, cm/yr					
Northern Plains†						
Wheat	0.74	0.25	0.13	0.08	0.05	0.03
Fallow	0.01	0	0	0	0	0
W. Kans.-E. Colo.						
Wheat	2.84	0.97	0.53	0.30	0.23	0.18
Fallow	0.20	0.01	0	0	0	0
W. Texas						
Wheat	4.01	1.42	0.79	0.43	0.36	0.25
Fallow	1.94	0.23	0.07	0.02	0.01	0.01
Iowa‡	0.28	0.10	0.05	0.03	0.03	0.03
	Wheat-sorghum-fallow rotation, cm/yr					
Nebr.-S. Dak.						
Wheat	1.40	0.53	0.30	0.18	0.13	0.10
Sorghum	0.01	0	0	0	0	0
Fallow	1.31	0.49	0.27	0.16	0.12	0.09
W. Kans.-E. Colo						
Wheat	3.40	1.35	0.79	0.46	0.38	0.28
Sorghum	0.20	0.01	0	0	0	0
Fallow	3.36	1.28	0.73	0.43	0.34	0.26
W. Texas						
Wheat	4.27	1.63	0.94	0.56	0.46	0.36
Sorghum	1.94	0.23	0.07	0.02	0.01	0.01
Fallow	4.10	1.47	0.82	0.47	0.37	0.28
Iowa §	0.61	0.25	0.15	0.10	0.08	0.05

*See Table 2 for description of wind erodibility groups.
†N. Dak., S. Dak., Nebr., Mont., Wyo.
‡Continuous corn
§No vegetative cover.

TABLE 4. ESTIMATED ANNUAL REDUCTION IN WHEAT YIELDS RESULTING FROM WIND EROSION UNDER TWO CROP ROTATIONS IN THE GREAT PLAINS

Location	Wind erodibility groups 1	2	3-4L	5	6	7
	Wheat-fallow rotation, kg/ha/yr					
Northern Plains*	15.1	5.2	2.8	1.6	1.2	0.8
W. Kans.-E. Colo.	60.3	19.5	10.7	6.0	4.8	3.6
W. Texas	118.3	33.0	17.1	9.1	7.5	5.2
	Wheat-sorghum-fallow rotation, kg/ha/yr					
Nebr.-S. Dak.	36.1	13.5	7.5	4.4	3.2	2.4
W. Kansas.-E. Colo.	92.1	34.9	20.2	11.9	9.5	7.1
W. Texas	136.6	44.1	24.2	13.9	11.1	8.7

*N. Dak., S. Dak., Nebr., Mont., and Wyo.

the growing wheat of the wheat year (plus some flat sorghum residue) provided almost as much erosion protection as did the standing sorghum of the fallow year.

Annual reductions in wheat yields, based on data in Table 1 and average data in Table 3, are contained in Table 4. Similar data for grain sorghum and corn are presented in Table 5. Differences among locations for the same WEG resulted largely from differences in climate (the C factor), although some resulted from variations in vegetative residues across the Plains. Obviously, potential soil losses by wind are greater from coarse-textured soils (WEG 1-2) than from medium- and fine-textured soils (WEG 3-7).

Data from Tables 4 and 5 were applied to Land Resource Area (LRA) 77 in the Oklahoma Panhandle (Table 6). This area was selected because data were available by WEG for the cultivated sandy surface soils, the soils most susceptible to wind erosion. The area was assumed to be similar to West Texas, with wheat occupying twice as much land as grain sorghum. The estimated annual yield reductions of 29,900 ql (106,600 bu) of wheat and 16,800 ql (66,100 bu) of grain sorghum are equivalent to a total crop failure on about 4,530 ha (11,200 acres or 17.5 sections) of these sandy surface soils (based on long-term crop yields). Less than 1 percent of WEG-1 soil in the LRA is cultivated, suggesting a strong recognition by land owners of the wind-erosion hazard.

Relating crop yield to soil thickness (excluding the effect of fertilizer) and determining potential annual soil loss from the wind erosion equation seem to be the only feasible approach currently available. Perhaps a few comments on isolating the effects of wind erosion on productivity (using historic grain yield as the indicator) would be appropriate. The coefficient of variation for long-term wheat yield averages 62 percent for Ford, Finney, and Greeley Counties in western Kansas. The corresponding value for grain sorghum is 52 percent; at Dalhart, TX, 69 percent. Suppose, given the variation in crop yield experienced in the past, one desires to determine the number of replications needed to detect a 34-kg/ha (0.5-bu/ac) difference in mean wheat yield in Ford County, KS. Using this equation given by Snedecor (1956):

$$n = (Q_{a,f})^2 \, S_o^2 \, F_{f_1 f_0} / \delta^2 \quad \ldots\ldots\ldots\ldots [7]$$

where

n = number of replications
Q = found in standard tables for a-treatments and f-degrees of freedom,
S_o = the standard deviation,
F = the variance ratio for $f_1 f_0$-degrees of freedom, and

TABLE 5. ESTIMATED ANNUAL REDUCTION IN GRAIN SORGHUM YIELDS RESULTING FROM WIND EROSION UNDER A WHEAT-SORGHUM-FALLOW ROTATION IN THE GREAT PLAINS AND CORN YIELD REDUCTION IN IOWA UNDER FALL PLOWING

Location	Wind erodibility groups 1	2	3-4L	5	6	7
	kg/ha/yr					
Nebr.-S. Dak.	54.0	20.2	11.3	6.5	4.7	3.6
W. Kans.-E. Colo.	137.6	52.2	30.2	17.8	14.2	10.7
W. Texas	204.0	65.8	36.2	20.8	16.6	13.0
Iowa*	58.8	24.1	14.5	9.6	7.7	4.8

*Corn yield reductions under no vegetative cover conditions.

TABLE 6. ESTIMATED ANNUAL CROP YIELD REDUCTION RESULTING FROM WIND EROSION ON SANDY SURFACE SOILS IN THE OKLAHOMA PANHANDLE (LRA 77*)

WEG	Area, ha	Wheat yield reduction kg/ha	Wheat yield reduction ql	Area, ha	Grain sorghum yield reduction kg/ha	Grain sorghum yield reduction ql
1	113	136.6	154.4	57	204.0	116.3
2	17,155	44.1	7,565.4	8,580	65.8	5,645.6
3	91,603	24.2	22,167.9	45,803	24.1	11,038.5
Total	108,871		29,887.7	54,440		16,800.4

*Land Resource Area 77 in Oklahoma includes all of Cimarron and Texas Counties and the western one-fourth of Beaver County.

δ = the difference to be detected,

the number of replications (at the 5 percent probability level) needed is 2,077! To detect a 63-kg/ha (1 bu/ac) difference in mean grain sorghum yield at Dalhart, TX, would require 2,337 replications.

Additional research on "benchmark" soils of the Great Plains in controlled studies should be directed toward obtaining precise yield-soil thickness data. Data are also needed on distribution of soils by WEG and land use plus crop distributions according to WEG on cultivated land on a county or LRA basis for areas susceptible to wind erosion.

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