WIND EROSION IN DESERTS :

SURFACE SUSCEPTIBILITY AND CLIMATIC EROSIVITY

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ABSTRACT

Deserts are especially vulnerable to the ravages of wind erosion. Because of the sparsity of vegetation, low precipitation, and often nonaggregated surface materials, erosion is almost certain during periods of high wind speed. Wind erosion removes the fine, most fertile portion of the soil and contributes it to the atmospheric dust load. The source strength of mineral dust of the Sahara Desert is estimated at 260 million tons per year. With the suspension size particles removed, the material remaining is more difficult to aggregate, more easily shifted by the wind, and less suitable for establishing vegetation. Mechanics of wind erosion, influence of precipitation, and wind speed probability distributions are used to evaluate climatic tendency to produce conditions conducive to wind erosion. Most deserts are so arid that the surface is almost always dry, and wind speed dominates the climatic influence on wind erosion.

INTRODUCTION

Arid lands comprise about one-third of the world's total land area and are the home of one-sixth of the world's population (Dregne, 1976; Gore, 1979). The inhabitants of those arid lands not only cope with existing deserts but the threat of further desertification of their homelands by the expanding deserts.

Land undergoing desertification becomes vulnerable to wind erosion and associated dust storms (Secretariat of UNCOD, 1977, p. 14). Extensive aeolian deposits from past geologic eras prove that this is not a recent phenomenon. Wind erosion in deserts and arid lands (sparse vegetation and loose, dry, finely divided surface material) occurs almost unabated when speed exceeds thresholds. Agricultural land most susceptible to wind erosion includes much of North Africa and the near east, parts of southern and eastern Asia, the Siberian Plains, Australia, southern South America, and the semiarid and arid portions of North America (FAO, 1960).

Drought and over-grazing increase vulnerability of the land to wind erosion. On pastoral rangeland, composition of pastures subject to excessive grazing during dry periods deteriorates, the proportion of edible perennial plants decreases, and the proportion of annuals increases. The thinning and death of vegetation during dry seasons increase the extent of bare ground, and surface soil conditions deteriorate, increasing the fraction of erodible aggregates on the soil surface. In rain-fed farming areas, removal of the original vegetation and fallow periods between crops expose the soil to accelerated wind erosion.

Wind erosion physically removes from the field the most fertile portion of the soil and, therefore, lowers productivity of the land (Daniel and Langham, 1936; Lyles, 1975). Some soil from damaged lands enters suspension and becomes part of the atmospheric dust load. Hagen and Woodruff (1973) estimated that eroding lands of the Great Plains contributed 244 and 77 million tons of dust per year to the atmosphere in the 1950s and 1960s, respectively. Jaenicke (1979) estimated the source strength of mineral dust form the Sahara at 260 million tons per year. Dust obscures visibility and pollutes the air, causes automobile accidents, fouls machinery, and imperils animal and human health. Blowing soil fills road ditches, reduces seedling survival and growth; lowers the marketability of vegetable crops like asparagus, green beans, and lettuce; increases the susceptibility of plants to certain types of stress including diseases; and contributes to transmission of some plant pathogens (Hayes, 1966, 1972; Claflin et al., 1973).

SURFACE SUSCEPTIBILITY

Desert surface materials erode, then are detached and transported by the wind when more force is exerted on the materials than they can withstand. The surface material resists detachment and transport if the particles are dense, large, and consolidated and the wind is not reinforced with abrader projectiles. Also, the surface may be protected from the shear stress of the wind by nonerodible elements. Small stones, clods, large aggregates, growing plants, and plant residue can absorb the forces of the wind, thus, preventing the small erodible particles from eroding.

From wind tunnel tests, Chepil (1950) determined relative erodibilities of soils as a function of proportions of dry soil aggregates in various sizes. Clods larger then 0.84 mm in diameter were nonerodible in the range of wind speeds used in the tests. Since then, the nonerodible soil fraction > 0.84 mm, as determined by dry sieving, has been used to indicate erodibility of soil by wind.

Relative wind tunnel erodibility was converted to actual soil loss in a series of field experiments on 69 fields in the vicinity of Garden City, Kansas, USA (Chepil, 1960). The results of this conversion are given in Table 1.

Table 1: Soil erodibility for soils with different percentages of nonerodible fractions as determined by standard dry sieving (Woodruff and Siddoway, 1965)

	Percentage of dry soil fractions > 0.84 mm									
Tens	0	1	2	3	4	5	6	7	8	9
	Mg/ha									
0	-	695	560	493	437	404	381	359	336	314
10	300	294	287	280	271	262	253	244	238	228
20	220	213	206	202	197	193	186	182	177	170
30	166	161	159	155	150	146	141	139	134	130
40	126	121	117	114	112	108	105	101	96	92
50	85	80	75	70	65	61	28	54	52	49
60	47	45	43	40	38	36	36	34	31	29
70	27	25	22	18	16	13	9	7	7	4
80	4	-	-	-	-	-	-	-	-	-

Where soil erodibility is the potential soil loss in Mg/ha per year from a wide, unsheltered, isolated field with a bare smooth surface for the climatic conditions existing in the vicinity of Garden City, Kansas.

Most sand grains such as in desert dunes, are smaller than 0.84 mm and, therefore, are highly susceptible to erosion from strong wind. Because of relatively large fraction of dry soil aggregates > 0.84 mm, erodibility of an aggregated surface is much less than that of single-grain sand. However, erodibility of aggregated material is extremely dynamic and varies seasonally, yearly, and as the result of several management operations.

The aggregate status of the soil at any instant of time is the result of many aggregate-forming and degrading processes. Those processes comprise a complex interrelationship of physical, chemical, and biological reactions. Aggregation may involve the breakdown of clods into more favorable size or the formation of aggregates from finer materials.

Another factor to be considered in assessing or predicting the aggregate status or erodibility of a soil is the influence of cropping history and tillage. Soils broken out of native sod lost much of their aggregation in the surface-tilled zone (Olmstead, 1946; Skidmore et al., 1975). Skidmore et al. (1986), in a study of soil physical properties as influenced by management of residues from winter wheat and grain sorghum, found that most of the soil physical properties measured were not influenced by either grain sorghum or wheat management treatments; however, the aggregate status differed between crops. The soil aggregates from sorghum plots were smaller, more fragile, less dense, and more wind erodible than aggregates from the wheat plots. Harris et al. (1966) reported that agronomic systems affect aggregation pronouncedly but that interpretion of controlling mechanisms is complicated by the diversity of factors through which the effects are manifest.

In spite of temporal variation of soil aggregate status, Woodruff and Siddoway (1965) suggested that soil erodibility can be estimated by standard dry sieving and use of table 1. Using sieving results assumes that the values determined (% > 0.84 mm) "characterize" a soil during the critical erosion period for the time domain of the wind erosion equation.

For determining percentages of dry soil fractions > 0.84 mm, Chepil and Woodruff (1959) recommended the rotary sieve. A conventional (and more readily available) flat sieve may be used, but the results are expected to be less accurate.

When using a flat sieve, the following procedure should be followed:

(1) Obtain 1 kg samples from 0-2 cm surface layer when soil is reasonably dry. If soil is not near air dryness, dry in laboratory before sieving.
(2) Weigh the sample and sieve it on a 0.84 mm (N°. 20), 20.3 cm (8 inch) diameter sieve, until the smaller than 0.84 mm diameter aggregates have passed through. Be careful not to fragment aggregates during sieving. Weigh the amount of sample remaining on the sieve.
(3) Calculate the mass fraction of the total sample that was retained on the sieve and use table 1 to determine soil erodibility.

Recently, Hagen et al. (1987) proposed using two sieve cuts to characterize dry aggregate size distribution. Whit this procedure, it is assumed that the aggregates are size distributed log-normally. The distribution is characterized by geometric mean diameter and geometric standard deviation.

As geometric mean diameter of the surface materials increases, so does the resistance of the surface to wind erosion, similar to the effect of increased percentages of aggregates greater than 0.84 mm. Various soil stabilizers have been evaluated to find materials and methods to bind the surface materials together and, thus, effectively increase size of aggregates and control wind erosion (Armbrust and Dickerson, 1971; Armbrust and Lyles, 1975; Chepil, 1955; Chepil and Woodruff, 1963; Chepil et al., 1963; Lyles et al., 1969; Lyles et al., 1974). Several tested products successfully controlled wind erosion for a short time but many were more expensive than the equally effective wheat straw anchored with a rolling disk packer (Chepil et al., 1963). The following are criteria for surface-soil stabilizers:

(1) 100 percent of the soil must be covered,
(2) the stabilizer must not adversely affect plant growth or emergence,
(3) erosion must be prevented initially and reduced for the duration of the severe erosion hazard, usually for at least two months each season,
(4) the stabilizer should apply easily and without special equipment,
(5) cost must be low enough for profitable use (Armbrust and Lyles, 1975).

Armbrust and Lyles (1975) found five polymers and one resin-in-water emulsion that met all those requirements. However, they noted that before soil stabilizers can be used on agricultural lands, methods must be developed to apply large volumes rapidly. Also, reliable preemergent weed-control chemicals for use on coarse-textured soils must be developed, as well as films that resist raindrop impact, yet still allow water and plant penetration without adversely affecting the environment.

Periodically, symposia (DeBoodt and Gabriels, 1976) are held on soil conditioning, including papers on some aspect of using soil conditioners for controlling wind erosion. DeBoodt (personal communication), Ghent, Belgium, believes that activating neutral sand surfaces with iron sulfate and stabilizing the surface with urea-formaldehyde has much promise as an inexpensive and effective method of controlling wind erosion on sandy soils.

VEGETATION

Native vegetation in desert environments is usually sparse or absent except in irrigated areas. When present, living vegetation or residue from harvested crops protects the surface against wind erosion. Standing vegetation provides nonerodible elements that absorb much of the shear stress in the boundary layer. When vegetation and crop residues are sufficiently high and dense to prevent intervening soil-surface drag from exceeding threshold drag, soil will not erode. Rows perpendicular to wind direction control wind erosion more effectively than do rows parallel to wind direction (Englehorn et al., 1952; Skidmore et al., 1966). Flattened stubble, though not so effective as standing, also protects the soil from wind erosion (Chepil et al., 1955).

Studies (Chepil, 1944; Chepil et al., 1955; Siddoway et al., 1965) to quantify specific properties of vegetative covers influencing wind erosion led to the relationship presented by Woodruff and Siddoway (1965), showing the influence of an equivalent vegetative cover of small grain and sorghum stubble for various orientations (flat, standing, height).

Efforts have continued to evaluate the protective role of additional crops (Craig and Turelle, 1964; Lyles and Allison, 1981), range grasses (Lyles and Allison, 1980), feedlot manure (Woodruff et al., 1974), and the protective requirements of equivalent residue needed to control wind erosion (Lyles et al., 1973; Skidmore and Siddoway, 1978; Skidmore et al., 1979).

Lyles and Allison (1980, 1981) found high single-correlation coefficients from an equation of the form:

$$(SG)_e = a\,R_w^{\,b} \qquad (1)$$

where $(SG)_e$ is flat small-grain equivalent R_w is the above-ground dry weight of the vegetation to be converted, both in kg/ha; a and b are constant coefficients for each vegetation type or crop. Prediction equation coefficients are given in the literature for crop residues (Lyles and Allison, 1981), range grasses (Lyles and Allison, 1980), growing crops (Armbrust and Lyles, 1985), and some desert shrubs (Hagen and Lyles, in press).

Fryrear (1985) investigated soil loss with various fractions of the surface covered with simulated flat residues (wood dowels) relative to soil loss from bare soil. He found that:

$$SLR = 1.81 \exp(-7.2\ SC) \qquad (2)$$

describes the relationship between soil loss ratio (SLR) and fractional soil cover (SC) with a correlation coefficient of -0.94. The cover can be any nonerodible material such as large clods, gravel, or crop residue.

CLIMATIC EROSIVITY

Wind erosion climatic erosivity is a measure of a climate is tendency to produce conditions conducive to wind erosion. Two climatic elements (wind and rain) greatly influence the intensity of erosion. Strong winds erode, and wetness decreases the susceptibility of the surface to erosion. Rain also enables one to generate nonerodible aggregates on cohesive soils with appropriate tillage. Particle-movement rate of dry, erodible particles is directly proportional to friction velocity cubed. As expressed by Bagnold (1943):

$$q = Ku_*^3 \qquad (3)$$

where q is mass flow rate, K is a proportionality constant, and u_* is friction velocity. Lettau and Lettau (1978) modified the Bagnold equation to account for no particle movement until the friction velocity exceeds a minimum or threshold:

$$q = K(U_* - U_{*t})\, U_*^2 \qquad (4)$$

where U_{*t} is threshold friction velocity.

Then to express the rate of erosion of damp material composed of all erodible particles, Chepil (1956) experimentally determined that adsorbed water increased threshold shear stress proportionally to equivalent water content squared. Equivalent water content was defined as volume fraction of water in the soil divided by the volume fraction of water in the same soil at -1500 J/kg potential (15 bars suction).

From that knowledge, Skidmore (1986) derived a physically based erosivity factor, which is directly proportional to q and gives the climatic tendency to produce conditions conducive to wind erosion:

$$CE = \rho\int_R^\infty [u_T^2 + (\gamma^1/\rho a^2)]^{3/2}\, f(u)du \qquad (5)$$

where ρ is the air density, a is a constant made up of other constants (von Karman, height of wind speed observation, roughness parameter), u is the horizontal wind speed, u_T is threshold wind speed, f(u) is a wind speed probability density function, and γ^1 is the cohesive resistance caused by water on the soil particles. Cohesive resistance is proportional to the square of water content relative to water content -1500 J kg^{-1}. Relative water content is approximated from the Budyko dryness ratio and the Thornthwaite PE index with similar results.

The lower limit of integration is defined by:

$$R = U_T^2 + \delta^1/\rho a^2 \qquad (5)$$

which says that no erosion occurs until wind speed exceeds a threshold for surface particles and overcomes the added cohesive resistance contributed by the wetness of the surface particles.

The wind speed probability density function in equation (5) may be expressed as Weibull distribution (Justus et al., 1976):

$$f(u) = [\tfrac{k}{c}]\,[\tfrac{u}{c}]^{k-1} \exp[-[\tfrac{u}{c}]^k] \qquad (6)$$

where k and c are the shape and scale parameters, respectively. Parameter c has units of velocity, and k is dimensionless. Weibull parameters can be determined from wind speed distribution summaries.

The equivalent water content for use in equation (5) was approximately the inverse of the dryness ratio, which is often used as an indicator of the aridity of an environment (Budyko, 1958; Hare, 1983). The dryness ratio at a given site indicates the number of times the net radiative energy could evaporate the mean annual precipitation. Semiarid zones where wind erosion is likely to be a serious problem have a dryness ratio between 2 and 7 (Hare, 1983). Areas with dryness ratios larger than 7 are in the desert and desert margin zones. Most of the Great Plains of the USA has dryness ratios between 2 and 5. The Sahara Desert in North Africa has a maximum dryness ratio as high as 200 (Henning and Flohn, 1977).

Henning and Flohn (1977) reasoned that because net radiation can be more clearly defined than potential evaporation for each spot on the surface of the Earth, the use of net radiation is preferred to potential evaporation as a climatological index. Hare (1977, 1983) preferred the dryness ratio as an index of aridity (1983).

The assumption that the dryness ratio approximates the equivalent content of the surface particles is reasonable and should be sufficient for a climatological index. However, for a more detailed analysis or flux equation, more research is needed to determine the relation of soil drying to wind-erodible dryness as a function of meteorological variables and soil hydraulic properties (Skidmore and Dahl, 1978).

Values calculated by equation (5) and compared to a wind-erosion climatological reference (Garden City, Kansas, USA) are shown in figure 1 as a function of dryness ratio for several mean wind speeds. As the dryness ratio increases, climatic erosivity increases but progressively at a slower rate until the dryness ratio approximates 10. After that, a further increase does not further increase the wind erosion hazard because of dryness of particles.

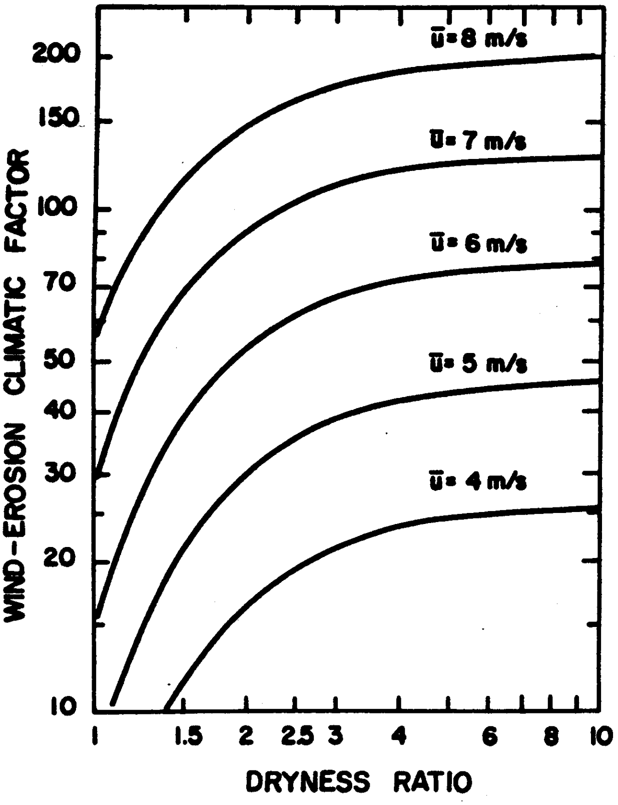

Figure 1: Climatic erosivity as influenced by dryness ratio and mean wind speed (after Skidmore, 1986)

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