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Wind erosion

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WIND erosion is a serious problem in many parts of the world. Extensive aeolian deposits from past geologic eras also prove it is not a recent phenomenon.

Wind erosion is worse in arid and semiarid areas where the following conditions frequently occur: loose, dry, finely divided soil; a smooth soil surface devoid of vegetative cover; large fields; and strong winds (*44*). Arid and semiarid lands are extensive. 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 (*37, 50*). Areas most susceptible to wind erosion on agricultural land include 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 (*44*).

Land undergoing desertification becomes vulnerable to wind erosion (*85*). 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 or droughts increase the extent of bare ground, and surface soil conditions deteriorate, increasing the fraction of erodible aggregates on the soil surface. In rainfed farming areas, removal of the original vegetation and fallow expose the soil to accelerated wind and water erosion.

Extensive soil erosion in the U.S. Great Plains during the last half of the 19th century and in the prairie region of western Canada during the 1920s warned of impending disaster. In the 1930s, a prolonged dry spell culminated in dust storms and soil destruction of disastrous proportions in the prairie regions of both western Canada and the Great Plains (*2, 62, 65, 76, 102*).

Wind erosion physically removes from the field the most fertile portion of the soil and, therefore, lowers land productivity (*35, 68*). Some soil from damaged land enters suspension and becomes part of the atmospheric dustload. Hagen and Woodruff (*54*) estimated that eroding land in the Great Plains contributed 244 million and 77 million tons of dust per year to the atmosphere in the 1950s and 1960s, respectively. Jaenicke (*63*) estimated the source strength of mineral dust from the Sahara at 260 million tons a year. Dust obscures visibility and pollutes the air, causes automobile accidents, fouls machinery, and imperils animal and human health. Blowing soil also fills road ditches; reduces seedling survival and growth; lowers the marketability of vegetable crops, such as 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 (*33, 58, 59*).

Soil erodibility by wind

Scientists recognized early that soil erodibility, the susceptibility or ease of detachment and transport by wind, was a primary variable affecting wind erosion. From wind tunnel tests, Chepil (*17*) determined relative erodibilities of soils reasonably free from organic residues as a function of apparent specific gravity and proportions of dry soil aggregates in various sizes. Clods larger than 0.84 mm in diameter were nonerodible in the range of windspeeds 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. In an early version of the wind erosion equation (*26*), the nonerodible soil fraction was one of three major factors developed from results obtained principally with a portable wind tunnel (*113, 114, 116*).

A dimensionless soil erodibility index, I, was based on the nonerodible fraction, the percentage of clods >0.84 mm in diameter (*22, 27*). The quantity of soil eroded in wind tunnel tests is governed by the tunnel's length and other characteristics. Therefore, erodibility was expressed on a dimensionless basis so that for a given soil and surface condition the same relative erodibility value would be obtained regardless of wind-tunnel characteristics (*24*). The soil erodibility index was expressed as follows:

$$I = X_2/X_1 \qquad [1]$$

where X_1 is the quantity eroded from soil containing 60 percent of clods > 0.84 mm and X_2 is the quantity eroded under the same set of conditions from soil containing any other proportion of clods > 0.84 mm. The soil erodibility index, I, gave a relative measure of erodibility, but actual soil loss by wind was not known.

Therefore, during the severe wind erosion seasons of 1954-1956, from January through April, Chepil studied 69 fields in western Kansas and eastern Colorado to determine the quantity of soil loss for any field erodibility as determined from various field conditions (*24*). The average depth of soil eroded usually was indicated by the depth to which crowns and roots of plants were exposed.

Seasonal loss was converted to annual soil loss, and relative field erodibility for each field was determined by procedures previously outlined (*23*, *26*, *27*). The relation between annual soil loss and relative field erodibility was as follows:

$$Y = aX^b - 1/cd^x \qquad [2]$$

where Y is annual soil loss (tons/acre); X is the dimensionless relative field erodibility; and a, b, c, and d are constants equal to 140, 0.287, 0.01525, and 1.065, respectively. Chepil (*24*) recognized that inaccuracies in measuring relatively small annual soil losses from depth of soil removal made converting relative field erodibility to annual soil loss by equation 2 highly approximate.

When a field is smooth, bare, wide, unsheltered, and noncrusted, its relative erodibility is equal to the erodibility index defined by equation 1. To obtain potential annual soil loss in tons per acre, I is substituted for x in equation 2. Equation 2 was multiplied by one-third, then used to generate a table (*109*) for erodibility of soils with different percentages of nonerodible fractions > 0.84 mm (Table 1).

A more reliable and technically sound procedure is needed to estimate or predict the erodibility index without making physical measurements. This would save time and expense and provide a means to estimate erodibility more accurately.

In current practice, scientists often estimate soil erodibility by grouping soils, mostly according to predominant soil textural class (Table 2).

Because of the utility of predicting soil erodibility from easily obtainable soil properties, table 2, or a similar one, has been used extensively. Problems associated with using table 2 to estimate soil erodibility include the transience of dry soil aggregates > 0.84 mm within a given wind erodibility group (WEG).

Actual erodibility is extremely dynamic and varies seasonally, yearly, and as the result of management operations. In a study on the effects of season on soil erodibility, Chepil (*18*) found erodibility always was higher in the spring than in the previous fall if the soil had received moisture occasionally during the winter. But the increases were not of the same magnitude for all soils. The greatest increase in erodibility from fall to spring occurred in the finest textured soil, the least in the coarsest. Sandy loam was highly erodible in both fall and spring. Clay was least erodible in the fall, but about as highly erodible as sandy loam in the spring. The intermediate-textured soils had an intermediate erodibility in both spring and fall.

Grouping is discontinuous and results in large, discrete jumps in erodibility with textural change. For example, the soil erodibility indexes for loamy very fine sand (WEG 2) and very fine sandy loam (WEG 3) are 300 and 193 Mg/ha/yr, respectively. All other soils classed in those wind erosion groups have the same erodibility indexes. Do they have the same erodibility? It would be better to predict percentage of aggregates > 0.84 mm and then use table 1. A procedure must be devised for realistically predicting dry soil-

Table 1. Soil erodibility, I, for soils with different percentages of nonerodible fractions as determined by standard dry sieving (*109*).

	Soil Erodibility by Percentage of Dry Soil Fractions >0.84 mm									
Percent	*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	-	-	-	-	-	-	-	-	-

aggregate status that accounts for yearly and seasonal fluctuations and dominant soil properties influencing erodibility.

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

Another factor to be considered in assessing or predicting the aggre-

Table 2. Descriptions of wind erodibility groups (*105*).

WEG	*Predominant Soil Texture Class of Surface Layer*	*Dry Soil Aggregates > 0.84 mm (%)*	*Wind Erodibility Index, I (Mg/ha)*
1	Very fine sand, fine sand, or coarse sand	1	695
		2	560
		3	493
		5	404
		7	359
2	Loamy very fine sand, loamy fine sand, loamy sand, loamy coarse sand, or sapric soil materials	10	300
3	Very fine sand loam, fine sandy loam, sandy loam, or coarse sandy loam	25	193
4	Clay, silty clay, noncalcareous clay loam, or silty clay loam with more than 35 percent clay content	25	193
4L	Calcareous loam and silt loam or calcareous clay loam and silty clay loam	25	193
5	Noncalcareous loam and silt loam with less than 20 percent clay content or sandy clay loam, sandy clay, and hemic organic soil materials	40	126
6	Noncalcerous loam and silt loam with more than 20 percent clay content or noncalcereous clay loam with less than 35 percent clay content	45	108
7	Silt, noncalcareous silty clay loam with less than 35 percent clay content, and fibric organic soil material	50	85
8	Soils not susceptible to wind	>80	0

gate status or erodibility of a soil is the influence of cropping history and tillage. Page and Willard (*82*) found that the degree of aggregation in a corn/oats/alfalfa-bromegrass/alfalfa-bromegrass rotation is two to three times greater than that for continuous corn. Cropping systems that included continuous small grain, continous row crops, and rotations including fallow showed no significant differences in water-stable aggregation (*81*). Soils broken out of native sod lost much of their aggregation in the surface-tilled zone (*81, 92, 100*). Skidmore and associates, in a study of soil physical properties as influenced by management of residues from winter wheat and grain sorghum, found that grain sorghum or wheat management treatments did not influence most of the soil physical properties measured (*92*). However, the aggregate status differed among crops. Soil aggregates from sorghum plots were smaller, more fragile, less dense, and more wind-erodible than aggregates from wheat plots. Harris and associates (*57*) reported that agronomic systems affect aggregation significantly but that interpreting controlling mechanisms is complicated by the diversity of factors through which the effects are manifest.

Inability to predict both aggregate status and the weather undoubtedly influenced Woodruff and Siddoway's definition of soil erodibility (*109*): "the potential average annual soil loss from a wide, unsheltered, isolated field...for the climate in the vicinity of Garden City, Kansas." In spite of temporal variation of soil aggregate status, Woodruff and Siddoway suggested that soil erodibility can be estimated by standard dry sieving and use of table 1. Use of sieving results assumes that the values determined (percent > 0.84 mm) "characterize" a soil during the critical erosion period for the time domain of the wind erosion equation (*109*).

For determining percentages of dry soil fractions > 0.84 mm, Chepil and Woodruff (*27*) recommended the rotary sieve. A conventional and more readily available flat sieve may be used, but results with it are less accurate than with a rotating sieve.

Researchers should use the following procedure when using a flat sieve:

► Obtain 1 kg samples from the 0- to 2-cm surface layer when soil is reasonably dry. If soil is not near air dryness, dry it in the laboratory before sieving.

► Weigh the sample and sieve it on a 0.84-mm (No. 20), 20.3-cm (8-inch) diameter sieve until the aggregates < 0.84 mm diameter have passed through the sieve. Be careful not to fragment aggregates during sieving. Weigh the amount of sample remaining on the sieve.

► Calculate the mass fraction of the total sample that was retained on the sieve and use table 1 to determine soil erodibility.

Suppose from replicated sievings from a sample site that the total amount of air-dried soil for each sieving was 1,035, 945, 850, and 990 grams and the respective amounts retained on the 0.84 mm sieve after sieving were 370, 227, 200, and 250 grams. Therefore, percentages of dry soil fractions > 0.84 mm would be 26.1, 24.0, 20.7, and 25.3, respectively. Corresponding soil erodibility values from table 1 would be 186, 197, 213, and 193 Mg/ha, respectively; the mean would be 197 Mg/ha.

Wind erosivity

Chepil and associates (*25*) proposed a climatic factor to determine average annual soil loss for climatic conditions other than those occurring when the relationship between wind-tunnel erosion and field erosion was obtained. It is an index of wind erosion as influenced by moisture content in surface soil particles and average windspeed. The windspeed term of the climatic factor was based on the rate of soil movement being proportional to average windspeed cubed (*8, 15, 115*). The soil moisture term was developed on the basis that the erodibility of soil varies inversely with the square of the equivalent water content in the near-surface soil, which was assumed to vary as the Thornthwaite index (*20*).

The climatic factor was expressed as follows:

$$C = 386\frac{\bar{u}^3}{(PE)^2} \qquad [3]$$

where $\bar{u}$ is the mean annual windspeed corrected to 9.1 m and PE is the Thornthwaite (*103*) index. The 386 value indexes the factor to conditions at Garden City, Kansas.

Thornthwaite developed the climatic index to evaluate precipitation effectiveness. An equation was fitted to rather limited data that expressed the P/E ratio to temperature and precipitation as follows:

$$P/E = 0.316\left(\frac{P}{1.8T+22}\right)^{10/9} \qquad [4]$$

where P is the mean monthly precipitation in mm, E is the monthly evaporation in mm, and T is temperature in C°. Monthly values were added to obtain an annual value, which was multiplied by 10 to give:

$$\text{PE index} = 3.16 \sum_{i=1}^{12} \left(\frac{P_i}{1.8T_i + 22} \right)^{10/9} \qquad [5]$$

Equation 5 was evaluated and used in equation 3 to determine climatic factors for wind erosion at many locations in the United States (*25, 69, 98*).

As the PE index gets smaller as precipitation declines, as in arid regions, the climatic factor in equation 3 approaches infinity. In application, an upper limit is set by restricting minimum monthly precipitation to 13 mm (*69*). Monthly climatic factors also were calculated using an annual PE index with monthly mean windspeed (*108*).

The Food and Agriculture Organization approached the problem of the climatic factor becoming a large value in arid conditions differently (*45*). Agency researchers modified the Chepil and associates' index (*25*) as follows:

$$C^1 = 1/100 \sum_{i=1}^{12} \bar{u}^3 \left(\frac{ETP_i - P_i}{ETP_i} \right) d \qquad [6]$$

where $\bar{u}$ is the mean monthly windspeed at a 2-m height, ETP is potential evapotranspiration, P is precipitation, and d is the total number of days in the month. In this case, as precipitation approaches zero, windspeed dominates the climatic factor. Conversely, as precipitation approaches ETP, the climatic factor approaches zero. The influence of soil water in the FAO version is less than the squared influence of soil water demonstrated by Chepil (*20*).

I handled the influence of soil water differently and included a windspeed probability density function as follows (*90*):

$$CE = \varrho \int_{R}^{\infty} \left[u^2 - R^2 \right]^{3/2} f(u)du \qquad [7]$$

where,

$$R = u_t^2 + \gamma^1/\varrho a^2 \qquad [8]$$

and CE is the wind erosion climatic erosivity, which is directly proportional to mass flow rate of an all erodible material; ϱ is air density; u and u_t are windspeed and threshold windspeed, respectively;

γ^1 is the cohesive resistance of absorbed water; and a is a combination of constants, $k/\ln(z/z_0)$, for $k = 0.41$, $z = 10$ m, $z_0 = 0.05$ m; thus, $a = 0.0774$.

The value for γ is approximated as follows:

$$\gamma = 0.5\,\psi^2 \qquad [9]$$

where ψ is the equivalent soil water content, fraction of water (by mass or volume) in the soil, divided by fraction of water in the same soil at −1,500 J/kg (*20, 90*). It was assumed that equivalent surface water content was approximated by the ratio of precipitation to potential evaporation. The ratio of precipitation to evaporation can be approximated by the Thornthwaite PE index or the inverse of the dryness ratio (*12, 56*). The dryness ratio, D, is defined as follows:

$$D = Rn/(LP) \qquad [10]$$

where Rn is net radiation, L is latent heat of evaporation, and P is precipitation. The dryness ratio at a given site indicates the number of times the net radiative energy could evaporate the precipitation over the same time interval.

The windspeed probability density function, equation 7, can be expressed as a Weibull distribution:

$$f(u) = (k/c)\,(u/c)^{k-1}\exp[-(u/c)^k] \qquad [11]$$

where c and k are scale and shape parameters, respectively. Parameter c has units of velocity and k is dimensionless (*3, 66*). Weibull parameters have been determined from windspeed distribution summaries at many locations in the U.S. Great Plains (*53*).

Equation 7, with f(u) defined by equation 10, can be integrated straightforwardly when $k = 2$ as follows:

$$CE = 1.33\varrho c^3 \exp\left[-R/c^2)\right] \qquad [12]$$

where R is defined by equation 8.

The summation procedure for evaluating equation 7 can be written as follows:

$$CE = \varrho \sum_{u_{i+0.5}^2 > R}^{n} \left(u_{i+0.5}^2 - R\right)^{3/2}\left[F\left(u_{i+1}\right) - F\left(u_i\right)\right] \qquad [13]$$

where $F(u_i)$ is the cumulative distribution function:

$$F(u_i) = 1 - \exp\left[-(u_i/c)^k\right] \qquad [14]$$

When mean windspeed is available but the data from which the mean was calculated are not, the Weibull parameters can be estimated.

Studies have shown that the Weibull scale parameter was about 12 percent larger than mean windspeed and the Weibull shape parameter was a function of the scale parameter (*64*, *90*). Thus, if only mean windspeed is known, a reasonable estimate of Weibull distribution can be obtained as follows:

$$c = 1.12\ \bar{u} \qquad [15]$$

and

$$k = 0.52 + 0.23c \qquad [16]$$

Equations 7 and 13 express wind power, W m^{-2}. When multiplied by the time duration in the accounting period represented by f(u), they give erosive wind energy. This is the energy of the wind in excess of that necessary to overcome threshold shear stresses represented by R. Erosive wind energy is a useful parameter to evaluate the climatic factor for the wind erosion equation.

Suppose one wishes to know an appropriate climatic factor for a 30-day period of given conditions: mean windspeed = 5.8 m s^{-1}, average precipitation = 80 mm, net radiation = 490 MJ m^{-2}. Then, from equations 15 and 16, c and k are estimated to be 6.5 m s^{-1} and 2.0, respectively. The dryness ratio calculated from equation 10 is 2.5 for heat of vaporization of 2.45 MJ kg^{-1}.

Thus,

$$R = u_t^2 + \gamma/\varrho a^2 = 36 + 11 = 47\ m^2\ s^{-2} \qquad [17]$$

Equation 13 could be used to calculate CE. However, because k = 2.0, equation 12 was used to calculate CE as follows:

$$CE = 1.33\ \varrho c^3 \exp\left[-(R/c^2)\right] = 144\ W\ m^{-2} \qquad [18]$$

Therefore, the erosive wind energy for the 30-day period would be as follows:

$$CE \times time = 144\ W\ m^{-2} \times 8.64 + 10^4\ sd^{-1} \times 30d = 373\ MJ\ m^{-2} \qquad [19]$$

If the conditions given in this example 30-day period were to prevail for an entire year, then the erosive wind energy would be 4,538 MJ m^{-2}. That wind energy, compared to the reference of 8,100 MJ m^{-2}, gives a climatic factor of 56. Also, from figure 1, for

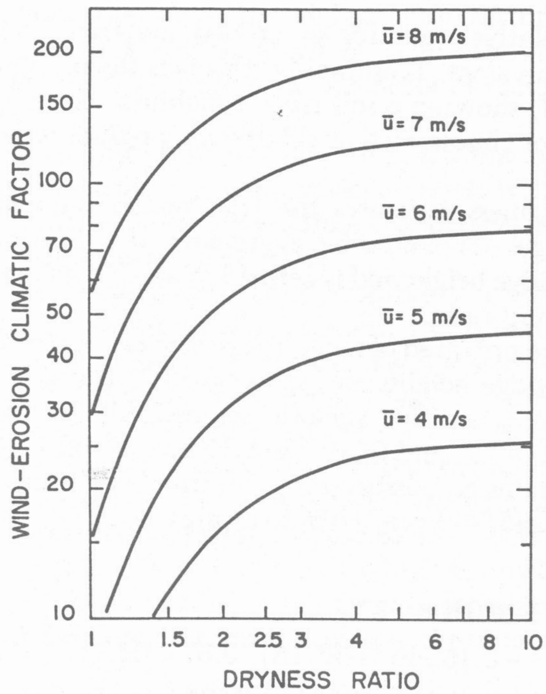

Figure 1. Wind erosion climatic factor as influenced by dryness ratio and mean windspeed (*90*).

a dryness ratio of 2.5 and a mean windspeed of 5.8 m s^{-1}, the climatic factor is 56.

Ridge roughness

Chepil and Milne (*32*) investigated the influence of surface roughness on intensity of drifting dune materials and cultivated soils. They found that the initial intensity of drifting was always much less over a ridged surface. Ridging cultivated soil reduced the severity of drifting, but ridging highly erodible dune material was less effective because ridges disappeared rapidly. The rate of flow varied inversely with surface roughness. Armbrust and associates (*7*) studied the effects of ridge-roughness equivalent on the total quantity of eroded material from soils exposed to different friction velocities. From their data, a curve can be constructed showing the relationtween the relative quantity of eroded material and the ridge-roughness equivalent. Presumably, this was the origin of the chart (*109*, *figure 4*) showing a soil ridge-roughness factor as a function of soil ridge roughness, so that ridging may reduce wind erosion up to 50 percent.

Ridge roughness estimates the fractional reduction of erosion caused by ridges of nonerodible aggregates. It is influenced by ridge spacing and ridge height and is defined relative to a 1:4 ridge-height-to-ridge-spacing ratio.

Tables were prepared of ridge-roughness factors for various combinations of ridge heights and spacings (*88*). Hayes (*60*) suggested evaluating fields as either smooth, semiridged, or ridged and then assigning 1.0, 0.75, and 0.50, respectively, as soil ridge-roughness factors. Williams and associates (*106*) fitted equations to the curve of Woodruff and Siddoway (*109*) to express the ridge-roughness factor as follows:

$$K = 1.0, \ HR^2/IR < 0.57 \quad [20]$$

$$K = 0.913 - 0.153 \ln (HR^2/IR), \ 0.57 < (HR^2/IR) < 22.3 \quad [21]$$

$$K = 0.336 \exp (.013 \ HR^2/IR), \ (HR^2/IR) \geq 22.3 \quad [22]$$

where HR and IR are ridge height and ridge spacing, respectively, in mm. A field with ridges 100 mm high and spaced 400 mm apart has $HR^2/IR = 25$. Because $25 > 22.3$ and using equation 22, the ridge-roughness factor $K = 0.5$.

Field length

Chepil and Milne (*32*) reported that the rate of soil movement started at zero on the windward side of fields or field strips and increased with distance downwind. Later, Chepil (*16*) found that the cumulative rate of soil movement with distance away from the windward edge of eroding fields was the main cause of steadily increasing amounts of erodible particles, increasing abrasion, and gradual reduction in the rate of soil flow with distance downwind "avalanching."

Rate of soil flow increased with distance downwind across an eroding field. If the field were large enough, soil flow reached the maximum that a wind of a given velocity could carry. Beyond that point, the rate of flow remained essentially constant (*21*). That maximum was about the same for soil of any texture—about 50 $gm^{-1}s^{-1}$ for a 17 $m\ s^{-1}$ wind at 10 m. The rate of increase for various soil textures was the same as the order of erodibility for soil texture classes.

The distance required for soil flow to reach the maximum that a wind of a given velocity can carry varies inversely with the erodibility of a field surface. The more erodible the surface, the shorter the distance to reach maximum flow (*23*).

Chepil (*23*) related relative wind erodibility to the distance required for soil flow to reach a maximum. In his earlier work (*16, 21, 32*), he presented data for the rate of soil movement as a function of distance from the windward edge of the field for soils that varied widely in erodibility. He converted the relative surface erodibility, based on four factors—soil cloddiness, crop residue, ridge-roughness equivalent, and soil erodibility—to relative field erodibility, based on additional factors—wind barrier, width of field, and wind direction (*23*). These functional relationships between field erodibility and field width with the many associated factors gave rise to how the field length term was used in the wind erosion equation (*28, 109*).

Originally, field length was considered as the distance across a field in the prevailing wind erosion direction (*109*). However, sometimes almost as much wind occurs from one direction as from another, so there is essentially no prevailing wind erosion direction. In these cases, researchers used the preponderance of wind erosion forces in the prevailing wind erosion direction to assess equivalent field length (*87, 98*). Later, from a more detailed analysis, tables were prepared that give wind erosion direction factors, numbers that when multiplied by field width give median travel distance as a function of preponderance of wind erosion forces in the prevailing direction and deviation of prevailing wind erosion direction from perpendicular to direction of field length (*90*).

In some of the modeling efforts, the procedure for determining L for use in the wind erosion equation was simplified by ignoring wind direction distributions. Cole and associates (*34*) suggested the following:

$$L = \begin{cases} w \sec\theta & L \le (l^2 + w^2)^{1/2} \\ l \csc\theta & \text{otherwise} \end{cases} \quad [23]$$

where w and l are the small and large dimensions, respectively, of a rectangular field and θ is the angle between side w and the prevailing wind erosion direction. As θ varies through $\pi/2$ radians, L will range from w to l, with a maximum equal to the main diagonal of the field. The procedure Williams and associates (*106*) used in EPIC, the erosion-productivity impact calculator, was as follows:

$$L = \frac{lw}{l|\cos(\pi/2 + \propto - \phi)| + w|\sin(\pi/2 + \propto - \phi)|} \qquad [24]$$

where l and w are the large (length) and small (width) dimensions, respectively, of a rectangular field, $\propto$ is the wind direction clockwise from north in radians, and ϕ is the clockwise angle between field length and north in radians. Using equation 24, L = 236 m for a rectangular field where $l = 1{,}000$ m, $w = 200$ m, $\propto = \pi/4$ radians, and $\phi = 0$.

Vegetative factor

Scientists realized early the value of crop residue for controlling wind erosion and reported quantitative relationships (*14*). From wind tunnel tests on plots especially prepared to obtain a range of vegetative cover and soil structure, Englehorn and associates (*39*) found the expotential relationship that best expressed their results. Subsequent studies (*19, 26, 27*) expressed the relationship in the form $x = aI/(RK)^b$, where x is the wind tunnel erodibility; I is the soil erodibility index (percent of clods > 0.84 mm); R is the dry weight of crop residue in pounds/acre; K is the ridge-roughness equivalent; and a and b are constants.

Amounts of wheat straw needed to protect most erodible dune sands and less erodible soils against strong winds were established (*31*). Standing stubble was much more effective than flattened stubble (*29*). Standing sorghum stubble with rows perpendicular to wind direction controlled wind erosion more effectively than rows parallel to wind direction (*39, 97*).

Siddoway and associates (*86*) quantified the specific properties of vegetative covers influencing soil erodibility and developed regression equations relating soil loss by wind to selected amounts, kinds, and orientation of vegetative covers, wind velocity, and soil cloddiness. They found a complex relationship among the relative effectiveness of different kinds and orientation of residue. The relative value of kinds and orientations of residue in controlling erosion must be qualified by soil, wind velocity, and variable characteristics of the residues. Generally, Siddoway and associates concluded that (a) on a weight basis, fine-textured residues were more effective than coarse-textured residues; (b) any orientation of residue, except flattened residue, reduced wind erosion; and (c) fine-leafed crops, such as grasses and cereals, provided a high degree of erosion control per unit weight.

Those studies led to the relationship developed by Woodruff and Siddoway (*109*) showing the influence of an equivalent vegetative cover of small grain and sorghum stubble for various orientations (flat, standing) and heights, then relating soil loss to equivalent vegetative cover.

Efforts to evaluate the protective role of additional crops have continued. In wind tunnel tests, Lyles and Allison (*70, 71*) determined equivalent wind erosion protection provided by selected range grasses and crop residues. They found high simple correlation coefficients from an equation of the form:

$$(SG)_e = aX^b \qquad [25]$$

where $(SG)_e$ is the flat small-grain equivalent, X is the quantity of residue or grass to be converted, and a and b are constants. Tables 3 and 4 show prediction equation coefficients.

It is not practical in testing all combinations of crops and residues to determine their protection value as flat small-grain equivalents. Therefore, a practice is needed to estimate the protection values of crops and residues not tested. Hayes (59) suggested that if any residue is not represented researchers should use a curve for the crop most like the crop in question.

Lyles and Allison (*71*) correlated measurable parameters, which describe crop residues, in several combinations to obtain an equation for predicting the flat small-grain equivalent of flat, random residues as follows:

$$(SG)_e = 0.162\ Rw/d + 8.708\ (Rw/d\gamma)^{1/2} - 271 \qquad r^2 = .92 \qquad [26]$$

where $(SG)_e$ is the flat small-grain equivalent (kg/ha), Rw is the residue amount to be converted (kg/ha), d is the average stalk diameter (cm), and γ is the average specific weight of the stalk (g/cm^3). Winter wheat, rape, soybeans, cotton, and sunflowers were used in developing equation 26.

Table 3. Coefficients in prediction equation $(SG)_e = aR_w^b$ for conversion of crop residues to an equivalent quantity of flat small-grain residue, both in kg/ha (*71*).

Crop Residue	Surface Orientation	Height (cm)	Length (cm)	Row Spacing (cm)	Row Orientation To Flow	Prediction a	Equation b	Coefficients r^2
Winter wheat	Standing	25.4	-	25.4	Normal	4.306	0.970	0.997
Rape	Standing	25.4	-	25.4	Normal	0.103	1.400	0.990
Cotton	Standing	34.3	-	76.2	Normal	0.188	1.145	0.998
Sunflowers	Standing	43.2	-	76.2	Normal	0.021	1.342	0.994
Winter wheat	Flat-random	-	25.4	-	-	7.279	0.782	0.993
Soybeans	Flat-random	-	25.4	-	-	0.167	1.173	0.993
Rape	Flat-random	-	25.4	-	-	0.064	1.294	0.997
Cotton	Flat-random	-	25.4	-	-	0.077	1.168	0.998
Sunflowers	Flat-random	-	43.2	-	-	0.011	1.368	0.993
Forage sorghum	Standing	15.9	-	76.2	Normal	0.353	1.124	0.995
Silage corn	Standing	15.9	-	76.2	Normal	0.229	1.135	0.998
Soybeans	1/10 standing	6.4	-	76.2	Normal	0.016	1.553	0.991
Soybeans	9/10 flat-random	-	25.4	-	-			

Table 4. Coefficients in prediction equation $(SG)_e = aX^b$ for conversion of range grasses to an equivalent quantity of flat small-grain residue, both in kg/ha (70).

Grass Species	*Grazing Management*	*Grass Height (cm)*	*Prediction a*	*Equation b*	*Coefficients r^2*
Blue grama	Ungrazed	33.0	0.60	1.39	0.98
Buffalograss	Ungrazed	10.2	1.40	1.44	0.97
Big bluestem	Properly grazed	15.2	0.22	1.34	0.99
Blue grama	Properly grazed	5.1	1.60	1.08	0.99
Buffalograss	Properly grazed	5.1	3.08	1.18	0.99
Little bluestem	Properly grazed	10.2	0.19	1.37	0.99
Switchgrass	Properly grazed	15.2	0.47	1.40	0.99
Western wheatgrass	Properly grazed	10.2	1.54	1.17	0.99
Big bluestem	Overgrazed	2.5	4.12	0.92	0.99
Blue grama	Overgrazed	2.5	3.06	1.14	0.99
Buffalograss	Overgrazed	1.5	2.45	1.40	0.99
Little bluegrass	Overgrazed	2.9	0.52	1.26	0.99
Switchgrass	Overgrazed	2.5	1.80	1.12	0.99
Western wheatgrass	Overgrazed	2.5	3.93	1.07	0.99

Until recently, all small-grain equivalence data have been limited to dead crop residue or dormant grass. Armbrust and Lyles (*6*) reported flat small-grain equivalents for five growing crops—corn, cotton, grain sorghum, peanuts, and soybeans, as follows:

$$(SG)_e = a_1 Rw^{b_1} \qquad [27]$$

where $(SG)_e$ is the flat small-grain equivalent and Rw is the aboveground dry weight of the crop to be converted, both in kg/ha, and a_1 and b_1 are constant coefficients for each crop. They found that if only rough estimates of $(SG)_e$ are needed, an average coefficient could be used. An average equation determined from pooling all crop data with rows running perpendicular to wind direction gave 8.9 and 0.9, respectively, for a_1 and b_1.

Suppose one wishes to know the equivalent flat small-grain residue for a field with grain sorghum growing in 400 kg/ha of flat, random winter wheat residue when the dry weight of the growing grain sorghum is 83 kg/ha and the grain sorghum is growing in rows perpendicular to the expected wind. Therefore, $(SG)_e$ for the growing sorghum, from equation 27, would be as follows:

$$(SG)_e = 8.9(83)^{.9} = 475 \qquad [28]$$

and, from table 3, $(SG)_e$ for the wheat residue would be

$$(SG)_e = 7.3(400)^{.8} = 880. \qquad [29]$$

However, because of nonlinear relationships, the flat small-grain equivalents are not strictly additive. When more than one crop contributes to the residue, it is better to combine the calculation into a single equation as follows:

$$(SG)_e = a_1^{p_1} a_2^{p_2} (Rwt)^{b_1 p_1 + b_2 p_2} \qquad [30]$$

where p_1 and p_2 are fractions of total residue, Rwt, and a_1, a_2 and b_1, b_2 are constant coefficients for respective crops as in equation 27. For our example as follows:

$$\begin{aligned}(SG)_e &= (8.9)^{.172}(7.3)^{.828}(483)^{(.9)(.172)\,+\,(.8)(.828)} \\ &= 1{,}190 \text{ kg/ha}\end{aligned} \qquad [31]$$

Either the equivalent flat small-grain or vegetative factor is needed for the various procedures to estimate wind erosion. The relationship between equivalent flat small-grain and vegetative cover was given graphically by Woodruff and Siddoway (*109*). Williams and associates (*106*) fitted an equation to the graphical relationship as follows:

$$V = 0.2533\ (SG)_e^{1.363} \qquad [32]$$

Therefore,

$$V = 0.2533\ (1{,}180)^{1.363} = 3{,}896\ \text{Mg ha}^{-1} \qquad [33]$$

A wind erosion model

Researchers and scientists have used a wind erosion equation proposed by Woodruff and Siddoway (*109*), with various modifications, for the past 20 years. The model was developed as a result of investigations to understand the mechanics of the wind erosion process, to identify major factors influencing wind erosion, and to develop wind erosion control methods. The general functional relationship between the independent variable E, the potential average annual soil loss, and the equivalent variables or major factors is as follows:

$$E = f(I, K, C, L, V) \qquad [34]$$

where I is the soil erodibility index, K is the soil ridge-roughness factor, C is the climatic factor, L is the unsheltered median travel distance of wind across a field, and V is the equivalent vegetative cover. These factors were discussed in more detail earlier.

Solving the functional relationships of the wind erosion equation as presented by Woodruff and Siddoway (*109*) required the use of tables and figures. The awkwardness of the manual solution prompted a computer solution (*43, 99*) and development of a slide-rule calculator (*89*).

The model has been adapted for use with personal computers (*55*) and interactive programs (*40*). Cole and associates (*34*) adapted the Woodruff and Siddoway (*109*) model for simulating daily soil loss by wind erosion as a submodel in EPIC (*106*). The latter version was simplified by fitting equations to the figures of Woodruff and Siddoway (*109*).

Solution of the wind erosion equation gives the expected amount of erosion from a given agricultural field. A second application of the equation is to specify the amount of erosion that can be tolerated and then solve the equation to determine the conditions required to limit soil loss to the specified amount, for example, the amount of residue, field width, etc. Conservationists have used the equation widely for both of these applications.

U.S. Soil Conservation Service field workers have used the equation extensively to plan wind erosion control practices (*59*). Hayes (*58*) also used the wind erosion equation to estimate crop tolerance to wind erosion. The equation is a useful guide to wind erosion control principles as well (*13, 80, 111*). Other uses of the equation include (a) determining spacing for barriers in narrow strip-barrier systems (*52*), (b) estimating fugitive dust emissions from agricultural and subdivision lands (*83, 107*), (c) predicting horizontal soil fluxes to compare with vertical aerosol fluxes (*49*), (d) estimating the effects of wind erosion on soil productivity (*67, 106*), (e) delineating those croplands in the Great Plains where various amounts of crop residues may be removed without exposing the soil to excessive wind erosion (*96*), and (f) estimating erosion hazards in a national inventory (*104*).

The following example of how to use the wind erosion equation to predict expected soil loss employs the variables used earlier, that is, $I = 197$ t $ha^{-1}yr^{-1}$; $K = 0.5$, $C = 56$, $L = 236$ m, and $V = 3.9$ Mg ha^{-1}. To determine the erosion estimate, however, requires a special combination of the factors. Several approaches are possible to find the solution: graphs, figures, tables, slide rule, or computer. Here, I use the procedure presented by Williams and associates (*106*). This procedure is done stepwise, but it has been simplified computationally by fitting equations to figures of Woodruff and Siddoway (*109*). The first step (E1) is to determine soil erodibility, I. Steps E2 and E3 are determined by multiplying the factors indicated as follows:

$$E2 = IK = 197 \times 0.5 = 93 \text{ Mg ha}^{-1} \text{ yr}^{-1} \quad [35]$$
$$E3 = IKC = 93 \times .56 = 52 \text{ Mg ha}^{1} \text{ yr}^{-1} \quad [36]$$

E4, the inclusion of field length, is

$$E4 = (WF^{0.348} + E3^{0.348} - E2^{0.348})^{2.87} = 33 \text{ Mg ha}^{-1} \text{ yr}^{-1} \quad [37]$$

where

$$WF = E2(1.0 - 0.122(L/Lo)^{-0.383} \exp(-3.33\ L/Lo) = 64 \quad [38]$$

and

$$Lo = 1.56 \times 10^{6}(E2)^{-1.26} \exp(-0.00156\ E2) = 4{,}465 \text{ m} \quad [39]$$

WF is a field length factor; it accounts for the influence of field length on reducing the erosion estimate. Lo is the maximum field length for reducing the wind erosion estimate.

Parameters Ψ_1 and Ψ_2 are functions of the vegetative cover factor described by the equations:

$$\Psi_1 = \exp(-0.759V - 4.74 \times 10^{-2}V^2 + 2.95 \times 10^{-4}V^3) = 0.026 \quad [40]$$

$$\Psi_2 = 1 + 8.93 \times 10^{-2}V + 8.51 \times 10^{-3}V^2 - 1.5 \times 10^{-5}V^3 = 1.469 \quad [41]$$

where V is in Mg ha^{-1} and for our example, from equation 33, has the value of 3.9 Mg ha^{-1}. Therefore,

$$E5 = \Psi_1 E4^{\Psi_2} = 0.026\ (33)^{1.469} = 4.4 \text{ Mg ha}^{-1} \text{ yr}^{-1} \quad [42]$$

The estimate of 4.4 Mg ha^{-1} yr^{-1} given by equation 42 is the annual rate of expected erosion during the 30-day period represented by the climatic factor C. To determine the expected erosion during the accounting period, it is necessary to multiple the given estimate by the fraction of the average annual total erosive wind energy occurring during the 30-day accounting period.

Management effects

Rough, cloddy surface. Tillage operations that leave furrows or ridges reduce wind erosion, as discussed earlier. When ridges are nearly gone, vegetative cover is depleted, and the threat of wind erosion continues, a rough, cloddy surface resistant to the force of wind can be created on many cohesive soils with appropriate "emergency tillage." For example, Lyles and Tatarko (*73*) found that chiseling of growing winter wheat on a silty clay soil greatly increased non-erodible surface aggregates without influencing grain yields. Farmers can use listers, chisels, cultivators, one-ways with two or three disks removed at intervals, and pitting machines to bring compact clods to the surface. Emergency tillage is most effective when done at right angles to the prevailing wind direction. Because clods eventually disintegrate, sometimes rapidly, emergency tillage offers only temporary wind erosion control at best (*111, 112*).

Residue. Living vegetation or residue from harvested crops protects the soil against wind erosion. Standing crop residues provide 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 (*39, 97*). Flattened stubble, though not as effective as standing stubble, also protects the soil from wind erosion (*29*).

Soon after the disastrous "dirty thirties" in the U.S. Great Plains, researchers demonstrated that stubble-mulching was a feasible method of reducing wind erosion on cultivated land (*38*). Stubble-mulching is a crop residue management system using tillage, generally without soil inversion, usually with blades or V-shaped sweeps (*77, 78*).

Other reduced and modified tillage systems have evolved with efforts to maintain residue on the soil surface. Chemical fallow (*11*) and ecofallow (*41*) systems use herbicides or herbicides and subsurface tillage during fallow periods to conserve a large quantity of residue on the surface.

Directly seeding small grains and other crops into stubble without a fallow period and without tillage is being studied and shows promise. The advantages of this system, compared with the tillage systems designed to preserve residues on the surface, include the following: (a) the standing stubble is needed for erosion control until the seeded crop produces enough cover to control erosion; (b) standing stubble more effectively controls erosion than does an equal quantity of flattened residue; (c) standing stubble, because it is not in direct contact with the soil, is less subject to decomposition than is stubble that has been tilled and mixed with the soil; and (d) without tillage, the soil is not pulverized.

The goal is to leave a desirable quantity of plant residue on the soil surface at all times. Residue is needed for a period of time after the crop is planted to protect the soil from erosion and improve water infiltration. The residue used is generally that remaining from a previous crop. Efforts continue to evaluate the residue needed to control wind erosion (*75, 91, 96*).

Stabilizers. Researchers have evaluated various soil stabilizers to find suitable materials and methods to control wind erosion (*4, 5, 19, 28, 30, 72*). Several tested products successfully controlled wind erosion for a short time, but many were more expensive than equally effective wheat straw anchored with a rolling disk packer (*30*). The following are criteria for surface-soil stabilizers: (a) 100 percent of the soil surface must be covered, (b) the stabilizer must not adversely affect plant growth or emergence, (c) erosion must be prevented initially and reduced for at least two months, (d) the stabilizer should be easy to apply and not require special equipment, and (e) cost must be low enough for profitable use (*5*). Armbrust and Lyles (*5*) found five polymers and one resin-in-water emulsion that met all of these requirements. They added, however, that before soil stabilizers can be used on agricultural land, 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 are resistant to raindrop impact while allowing water and plant roots to penetrate the soil, without adversely affecting the environment.

Barriers. Use of wind barriers is an effective method of reducing field width to control wind erosion (*9*). Hagen (*51*) and Skidmore and Hagen (*93*) developed a model that when used with local wind data shows wind barrier effectiveness in reducing wind erosion forces. Barriers will reduce wind erosion forces more than they will windspeed. A properly oriented barrier, when winds predominate from a single direction, will reduce wind erosion forces by more than 50 percent from the barrier leeward to 20 times its height; the reduction will be greater for shorter distances from the barrier.

Different combinations of trees, shrubs, tall-growing crops, and grasses can reduce wind erosion. Aside from conventional tree windbreaks (*42, 84, 110*), many other barrier systems are used to control wind erosion. They include annual crops, such as small grains, corn, sorghum, sudangrass, sunflowers (*13, 47, 48, 52, 61*); tall wheatgrass (*1, 10*); sugarcane; and rye strips on sands (John Griffin, SCS agronomist, Gainesville, Florida, personal communication, 1975).

Most barrier systems for controlling wind erosion, however, occupy space that could otherwise be used for crop production. Perennial barriers grow slowly and often are difficult to establish (*36, 110*). Such barriers also compete with crops for water and plant nutrients (*74*). As a result, the net effect of many tree-barrier systems is that their use may not benefit crop production (*46, 79, 94, 95, 101*).

Perhaps tree-barrier systems could be designed so that they become a useful crop, furnishing nuts, fruit, or wood.

Stripcropping. The practice of farming land in narrow strips on which the crop alternates with fallow is an effective aid in controlling wind erosion (*21*). Strips are most effective when they are at right angles to the prevailing wind direction, but they also provide some protection from winds that are not perpendicular to the field strip.

Stripcropping reduces erosion damage by reducing the distance the wind travels across exposed soil, localizing drifting that starts at a focal point, and reducing wind velocity across the strip when adjacent fields are covered with tall stubble or crops.

Although each method to control wind erosion has merit and application, establishing and maintaining vegetative cover, when feasible, remains the best defense against wind erosion. However, that becomes a difficult challenge as pressure increases to use crop residues for livestock feed and fuel for cooking.

Conclusions

Investigations of the factors influencing wind erosion led to the development of a wind erosion equation. The two-fold purpose of the wind erosion equation is to predict average annual soil loss from a field for specified conditions and to guide the design of wind erosion control practices.

Principles suggested by the wind erosion equation for controlling wind erosion include stabilizing erodible surface soil with various materials; producing a rough, cloddy surface; reducing field width or the distance wind travels in crossing a field unprotected with barriers and strips of crops; and establishing and maintaining sufficient vegetative cover. This last item is sometimes referred to as the "cardinal rule" for controlling wind erosion.

Although the wind erosion equation is extremely useful and widely applicable, users are cautioned that the value obtained for E is an estimate of average annual potential soil loss. The actual soil loss may differ from the potential because of (a) variation from the average of wind and precipitation, (b) inaccuracies in converting from relative field erodibility to annual soil losses, (c) relationships among variables not well defined for all combinations of field and climatic conditions, (d) seasonal variation of field erodibility, and (e) uncertainties inherent in the empiricism used in developing the equation.

Research in progress to improve the accuracy and applicability of the wind erosion equation includes:

► Determining the percentage of eroding soil that can be suspended during erosion under a wide range of field conditions and the residence time and fate of the various sizes of particles suspended by wind erosion.

► Refining the soil moisture term of the climatic factor, C, in the wind erosion equation. The current procedures assume that effective moisture of the surface soil particles varies with the PE index or dryness ratio, but surface moisture content is transient. Drying rate and dryness of particles, as a function of soil hydraulic properties and climatic variables, need to be examined and then related to the wind erosion process.

► Converting wind erosion prediction from a deterministic to a stochastic model by incorporating probability functions for some of the dynamic variables.

► Developing more applicable flux equations that can be integrated over time and space to predict soil erosion during single windstorms. Soil flux from fields that contain nonerodible elements decreases with time, which suggests that a time function is needed in the prediction equation.

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