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A WIND EROSION EQUATION: DEVELOPMENT, APPLICATION, AND LIMITATIONS

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ABSTRACT

This paper reviews briefly the development of a wind erosion equation from approximately 30 years of research to delineate major causes of wind erosion. Soil loss in tons per acre per year is predicted as a function of field width, soil erodibility, soil roughness, climate, and vegetation. Soil erodibility decreases as percentage of nonerodible soil fractions exceeding 0.84 mm increases. Rough surfaces are less erodible than smooth ones. The climatic factor is an index of the influences of moisture content in the surface soil particles and the average windspeed on the rate soil is moved by wind. The rate at which soil moves increases with distance downfield until maximum flow is reached. Fine-textured, standing residues reduce wind erosion more than do coarse-textured or flattened residues.

The equation was designed to determine potential erosion from a particular field, and the field conditions of soil cloddiness, roughness, vegetative cover, and sheltering by barriers necessary to reduce potential erosion to a tolerable amount. The equation has been used widely for those purposes and several others. Some sources of error in using the equation are: 1) Variation of wind and precipitation from the average, 2) inaccuracies in converting from relative field erodibility to annual soil loss, 3) relationships among variables not defined for all combinations of field and climatic conditions, 4) seasonal variation of field erodibility, and 5) inherent uncertainties in the empiricism of the equation development. Research that would further enhance the utility of the equation includes: 1) Determining the percentage of eroded material that enters suspension, 2) converting from a deterministic to a stochastic model, 3) applying the equation to single windstorms, and 4) adjusting the equation to apply to large-scale, rather than single field sites.

Wind erosion is severe in many areas of the United States and the world. It is the dominant problem on about 30 million hectares of land in the U.S. On the average, about 2 million hectares are moderately to severely damaged each year. Some soil from damaged lands enters suspension and becomes part of the atmospheric dustload. Hagen and Woodruff[1] estimated that eroding lands of the Great Plains contributed 244 and 77 million tons of dust per year to the atmosphere in the 1950's and 1960's, respectively. Since the dust bowl days of the "dirty thirties," numerous studies to understand the mechanics of the wind erosion process, identify major factors influencing wind erosion, and develop wind erosion control methods have led to the development of a wind erosion equation.[2]

This paper presents the state-of-the-art and science of the wind erosion equation by tracing its development and identifying its applications and limitations.

ERODIBILITY INDEX

Soil erodibility (ease of detachment and transport by wind) was recognized early as a primary variable affecting wind erosion. From wind tunnel tests, Chepil[3] 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 diam were nonerodible in the tests. Since then, the nonerodible soil fraction greater than 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,[4] it was one of three major factors developed from results obtained principally with a portable wind tunnel.[5,6,7]

A dimensionless soil-erodibility index, I,[8,9] was based on the nonerodible fraction (percentage of clods exceeding 0.84 mm diam). The quantity of soil eroded in a tunnel 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.[10] The soil erodibility index was expressed as

$$I = X_2/X_1 \qquad (1)$$

where X_1 is the quantity eroded from soil containing 60 percent of clods exceeding 0.84 mm, and X_2 is the quantity eroded under the same set of conditions from soil containing any other proportion of clods exceeding 0.84 mm. 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 1954-56, 69 fields were studied from January 1 through April 1 in western Kansas and eastern Colorado to determine the quantity of soil loss (tons per acre per year) for any field erodibility as determined from various field conditions.[10] The average depth of soil eroded usually was indicated by depth to which wheat crowns and roots were exposed.

Seasonal loss was converted to annual soil loss, and relative field erodibility for each field was determined by procedures previously outlined.[4,9,11] The relation between annual soil loss and relative field erodibility was

$$Y = aX^{b} - 1/cd^{X} \tag{2}$$

where Y is annual soil loss (tons per acre), X is dimensionless relative field erodibility, and a, b, c, and d are constants equal to 140, 0.287, 0.01525, and 1.065, respectively. Chepil[10] recognized that inaccuracies in measuring relatively small annual soil losses from depth of soil removal made conversion of relative field erodibility to annual soil loss by Eq. 2 highly approximate.

When a field is smooth, bare, wide, unsheltered, and noncrusted, its relative erodibility is equivalent to the soil erodibility index defined by Eq. 1. When I is substituted for X in Eq. 2, potential annual soil loss in tons per acre is obtained. Eq. 2 was multipled by 1/3 to account for natural crusting of soils and then used to generate Woodruff and Siddoway's table[2] for erodibility of soils with different percentages of nonerodible fractions exceeding 0.84 mm. Soil erodibility index (I) is multiplied by a factor to account for increased erodibility of knolls on windward slopes of less than 150 m.

RIDGE ROUGHNESS FACTOR

Chepil and Milne,[12] investigating the influence of surface roughness on intensity of drifting dune materials and cultivated soils, found that the initial intensity of drifting was always much less over a ridged surface. Ridging cultivated soils reduced the severity of drifting, but ridging highly erosive dune materials was less effective because the ridges disappeared rapidly. The rate of flow varied inversely with surface roughness.

Early versions of the wind erosion equation[4,9,13] contained a ridge roughness equivalent as the product of residue and ridge roughness.

Because it was difficult to determine surface roughness by measuring surface obstructions, Zingg and Woodruff[7] devised a method to determine surface roughness from pressure relationships in a wind-tunnel duct. The roughness was controlled by constructing ridges of nonerodible gravel. They varied the height of ridges progressively from

1.3 to 15.2 cm with a 1-to-4 ratio of ridge height to spacing. This calibration of a portable wind tunnel was used to evaluate ridge roughness equivalent for many field surfaces.[13]

As the wind erosion equation evolved, the influences of soil ridge roughness and vegetative cover were distinguished and treated independently in more detail. Armbrust, Chepil, and Siddoway[14] studied the effects of ridge roughness equivalent on total quantity of eroded material from three simulated, cultivated soils exposed to different friction velocities. From their data, a curve can be constructed showing the relationship between relative quantity of eroded material and ridge roughness equivalent. Presumably, this was the origin of the chart (Fig. 4)[2] showing a soil ridge-roughness factor as a function of soil ridge roughness so that a ridge roughness equivalent of 6 cm reduces wind erosion 50%. As roughness increases to about 11 cm, the soil ridge-roughness factor remains about constant; then, with additional roughness, the effectiveness of ridges gradually decreases.

The Soil Conversion Service[15] evaluates fields as either smooth, semiridged, or ridged, depending on equivalent ridge roughness, and then assigns 1.0, 0.75, and 0.50, respectively, as soil ridge-roughness factors.

CLIMATIC FACTOR

To determine average annual soil loss for climatic conditions other than those occurring when the relationship between wind tunnel and field erodibility were obtained, Chepil, Siddoway, and Armbrust[16] proposed a climatic factor. It is an index of the average rate of soil movement by wind as influenced by moisture content in surface soil particles and average windspeed.

The soil moisture term of the climatic factor of the wind erosion equation was developed on the basis that erodibility of a soil varies inversely with the equivalent moisture in surface soil particles.[17] Effective moisture of the surface soil particles was assumed to vary as indicated by the Thornthwaite[18] P-E index developed to evaluate precipitation effectiveness. The P-E index is the sum of 12 monthly precipitations divided by evaporation ratios. Its validity was checked by comparisons with plant growth.

The windspeed term of the climatic factor is based on the rate of soil movement being proportional to windspeed cubed. Several researchers[19–21] have reported that when windspeed exceeds that required barely to move the soil, the soil movement rate is directly proportional to friction velocity cubed. Over a specified surface, windspeed and friction velocity are proportional.

The long-term average windspeed and soil moisture index at Garden City, Kansas, is the reference for the climatic factor. It is expressed as $C = 100u^3/2.9(P\text{-}E)^2$, where u is the corrected mean annual windspeed for a standard height of 30 feet, P-E is an index of equivalent moisture in surface soil particles, and 2.9 is the approximate average value of $u^3/(P\text{-}E)^2$ for Garden City, Kansas.

Monthly windspeeds are used in lieu of annual windspeeds to determine monthly C values for calculating erosion when plant damage or certain periods of the year are the major interest.[22] Climatic factor maps have been prepared for the major wind erosion areas of the United States.[23]

FIELD WIDTH

Chepil and Milne[24] reported that rate of soil movement began with zero on the windward side of fields or field strips and increased with distance downwind. Later Chepil[25] 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 erosive particles, increasing abrasion, and gradual decrease in surface roughness along the direction of wind. He called the increase in rate of soil flow with distance downwind "avalanching."

"Rate of soil flow increased with distance downwind across an eroding field until, if the field was large enough, it reached a maximum that a wind of a given velocity can carry. Beyond that point the rate of flow remained essentially constant."[26] That maximum was about the same for soil of any texture—about 2 tons per rod width per hr for a 40-mph wind at 50 ft. The rate of increase for various textured soils was the same as the order of erodibility of the soil textural classes.

The distance required for soil flow to reach the maximum that a wind of a given velocity can carry varies inversely with erodibility of a field surface. The more erodible the surface, the shorter the distance to reach maximum flow.[11] Although Chepil[11] related relative wind erodibility to the distance required for soil flow to reach a maximum, he did not explain how he obtained the relationship. Presumable it was developed from his earlier work[24–26] in which he presented data for rate of soil movement as a function of distance from the windward edge of the field for soils that varied widely in erodibility. The relative surface erodibility based on four factors (soil cloddiness, crop residue, ridge roughness equivalent, and soil abradability) was converted to relative field erodibility based on additional factors (wind barrier, width of field, and wind direction).[11] These functional relationships between field erodibility and field width with the many associated factors gave rise to the field-length term of the wind erosion equation.[2,27]

Since its publication, the wind erosion equation has had one modification incorporated into the field width term. Previously, field width was considered as the distance across a field in the prevailing wind erosion direction. Sometimes almost as much wind occurs from one direction as from any other, and thus there is essentially no prevailing wind erosion direction. Therefore, preponderance of wind erosion forces in the prevailing wind erosion direction is used to assess equivalent field width.[23,28]

VEGETATIVE FACTOR

Value of crop residue for controlling wind erosion was recognized early, and quantitative relationships were reported.[29] From wind tunnel tests on plots especially prepared to obtain a range of vegetative cover and soil structure, Englehorn et al.[30] found the exponential relationship that best expressed their results. Subsequent studies[4,9,13] expressed the relationship in the form $X = a\ I/(RK)^b$, where X is wind tunnel erodibility; I is soil erodibility index (percent of clods exceeding 0.84 mm); R is dry weight of crop residue in pounds per acre; K is ridge roughness equivalent; and a and b are constants.

Amounts of wheat straw needed to protect most erodible dune sand and less erodible soils against strong winds were established.[31,32] Standing stubble is much more effective than flattened stubble.[13] Standing sorghum stubble with rows perpendicular to wind direction controlled wind erosion much more effectively than rows parallel to wind direction.[30,33]

Siddoway, Chepil, and Armbrust[34] 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 relation between the relative effectiveness of different kinds and orientation of residue. The relative value of kinds and orientations of residue to control erosion must be qualified by soil, wind velocity, and variable characteristics of the residues. Generally they concluded that: 1) On a weight basis, fine-textured residues are more effective than coarse-textured residues, 2) any orientation of residue except flattened decreases wind erosion, and 3) fine-leafed crops, like grasses and cereals, provide a high degree of erosion control per unit weight.

Those studies led to the relationship developed by Woodruff and Siddoway[2] showing the influence of an equivalent vegetative cover of small grain and sorghum stubble for various orientations (flat, standing, height), then relating soil loss to equivalent vegetative cover. In determining the potential erosion from a particular field, one considers other variables affecting soil loss, i.e., soil erodibility, ridge roughness, climatic factor, and field length factor, before considering vegetative cover.

Craig and Turelle[35] presented equivalent vegetative cover for additional crops, including a figure for converting quantity of various crop residues (peanuts, soybeans, shredded cotton, guar, sesame, standing cotton stalks) to quantity of equivalent flat small grain residue. Hayes[36] suggests that if any residue is not represented, a curve for a residue most like it can be used. Woodruff et al.[37] developed an equation for converting cattle feedlot manure to flat, small grain, wind-erosion-control equivalent.

Recent research[38] indicates that if residue is standing and equidistantly spaced, much less residue is needed to control wind erosion than had been previously reported.

EQUATION AND APPLICATION

As a result of all the investigations, a wind erosion equation[2] containing 5 equivalent variables was developed. The 5 were derived by grouping some and converting others of 11 primary variables known to govern wind erodibility. The general functional relationship between the dependent variable, E, (the potential average annual soil loss in tons per acre) and the equivalent variables is: $E = f(I',C',K',L',V)$, where I' is a soil erodibility index; K' is a soil ridge roughness factor; C' is a climatic factor; L' is field length along the prevailing wind erosion direction; and V is equivalent quantity of vegetative cover. Relations among variables are complex, and a single equation that expresses E as a function of the dependent variables has not been devised. The equation was solved in a stepwise procedure involving graphical solutions.

Because of the many tables and figures required to solve the functional relationships of the equation, manual solution is cumbersome. The need to simplify it was recognized, and a computer solution was developed.[39,40] Other efforts to implement the use and improve the accuracy of the wind erosion equation include: evaluating the monthly climatic factor;[22,23] assessing wind erosion forces, prevailing wind erosion direction, and preponderance of wind erosion forces in prevailing wind erosion direction;[23,28] evaluating the erodibility of organic soils (Woodruff and Dickerson);* correlating feedlot solids with other types of vegetative cover;[33] improving trap-strip design; and evaluating the wind erosion equation in the design or evaluation procedures.[41]

*Wind Erosion Research Laboratory Annual Reports, 1971 and 1972.

The equation was designed as a tool to determine both the potential erosion from a particular field and the field conditions (soil cloddiness, roughness, vegetative cover, sheltering by barriers, or width and orientation of field) necessary to reduce potential erosion to a tolerable amount.[2] The information needed to assess potential soil loss from a field is: 1) Percentage of soil aggregates exceeding 0.84 mm, 2) windward knoll slope, 3) ridge height and spacing, 4) climatic factor, 5) angle of deviation of prevailing wind erosion direction from right angles to field strip, 6) preponderance of wind erosion forces in prevailing wind erosion direction, 7) height of wind barrier, if any, 8) field width, 9) quantity of vegetative cover, and 10) type of vegetative cover. Items 4 and 6 can be obtained from the literature[23] by month for many U.S. locations. Information for determining item 5 can be obtained from the same reference. To obtain the percentage of soil aggregates exceeding 0.84 mm (item 1), dry sieving is best; however, in practice, this percentage is often determined from wind erodibility groups, based on soil type or predominant soil textural class. Other factors can be measured in the field or estimated by comparing field conditions with similar field conditions for which the factors have been measured.

The solution of the wind erosion equation gives the expected amount of erosion in tons per acre per year from a given agricultural field. The second application of the equation is to specify the amount of erosion that can be tolerated and then solve the equation to determine conditions, i.e., amount of residue, field width, etc., to limit soil loss to the specified amount. The equation has been used widely for both of these applications.[2,23,40] The Soil Conservation Service has used the equation extensively to plan wind erosion control practices and to determine crop tolerance to wind erosion conditions.[14,36,42] The equation also is a useful guide to wind erosion control principles.[43–45] Other uses of the equation include: 1) Determining spacing for barriers in narrow strip-barrier systems;[46] 2) estimating fugitive dust emissions from agricultural and subdivision lands;[47,48] 3) predicting horizontal soil fluxes to compare with vertical aerosol fluxes;[49] and 4) estimating effects of wind erosion on productivity.[50]

LIMITATIONS AND ADDITIONAL RESEARCH NEEDED

Although the wind erosion equation is extremely useful and widely applicable, its users are cautioned that the value obtained for E is an estimation of average annual potential soil loss. The actual soil loss may differ from the potential because of: 1) Variation from the average of wind and precipitation, 2) inaccuracies in converting from relative field erodibility to annual soil losses,

3) relationships among variables not well defined for all combinations of field and climatic conditions, 4) seasonal variation of field erodibility, and 5) uncertainties inherent in the empiricism used in developing the equation.

Research needs to improve the accuracy and applicability of the wind erosion equation include:

1. 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.

2. 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 P-E index, but surface moisture content is transient.[51-53] Although a method to measure water content of surface soil particles is being developed,[51,54] drying rate and dryness of particles, as a function of hydraulic soil properties and climatic variables, need examining and then relating to the wind erosion process.)

3. Possibly converting the wind erosion equation from a deterministic to a stochastic model by incorporating probability functions for some of the dynamic variables.

4. Developing a more applicable flux equation to predict rates of soil erosion during single windstorms. Equations proposed for field soils involve many insufficiently defined parameters. Soil flux from fields that contain some nonerodible elements decreases with time, which suggests that a time function is needed in the prediction equation.

5. Adjusting the present equation so that it is applicable on a large scale rather than only to a field site.

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OPEN DISCUSSION

ENGELMANN: Have you any speculation or observations that would bear on the fate and transport of submicron plutonium oxide that is "attached" to host soil particles of multimicron size in soil prior to resuspension? Specifically, is the assumption that PuO_2 stays attached to host soil particles a reasonable assumption?

SKIDMORE: We have had no experience with PuO_2; therefore we have no basis to judge how tenaciously PuO_2 stays attached to soil particles.

ENGELMANN: Is erosion from a particular field selective as to density and shape of particle? For instance, are humus particles or cubic particles removed or left selectively?

SKIDMORE: Wind erosion may be selective. Threshold friction velocities are lower for fine (but greater than about 0.1 mm) and low-density particles. Since organic particles are low density, they would be removed before the mineral portion of the soil of similar size. Selective removal also tends to remove silt and clay and leave sands and gravels behind. If friction velocity is great enough that the entire soil mass is eroded, sorting is not likely. Nonselective removal by wind is associated primarily with loess which was already sorted and deposited from the atmosphere during past geologic ages.

ENGELMANN: If you haven't done so in your paper, would you list for the Proceedings the few summary publications that you recommend to the newcomer to this field?

SKIDMORE: The following papers present two reviews, wind erosion equation, information helpful in using wind erosion equation, use of a computer to solve wind erosion equation, and the last one gives a guide to wind erosion control practices.

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ONISHI: Since the wind erosion equation is similar to the Universal Soil Loss Equation for soil loss due to runoff water, the wind erosion equation also has similar deficiencies: 1) This is not based on a dynamic mechanics of soil loss, 2) this provides only total amount of soil loss and it is difficult to use this equation to solve the time variations of soil loss on the ground and in air together with a mathematical simulation method. Please comment on these points. These problems must be future topics to be investigated.

SKIDMORE: The wind erosion equation is used widely for estimating average annual soil loss from agricultural lands and determining the field conditions necessary to limit average annual soil loss to a specified amount. But it does not answer all the questions for which we would like answers. As you have recognized, we need to develop a flux equation to give time variation of soil loss as a function of the many variables affecting soil detachment and transport.

SLINN: Two questions. First, did you use u or $u-u_t$, where u_t is the threshold velocity, to get your climatic factor? Second, in a recent paper by Gillette, et al., they quoted an analytical expression for the erosion rate (depending on I, V, R, L, T′, etc., and referenced Chepil). I thought you used a similar expression in your Agr. Handbook publication, yet I thought I heard you say that no analytical formula was available. Please resolve this for me.

SKIDMORE: First question. u was used to determine climatic factor. Second question: The expressions I have seen quoted by Gillette, et al. were for wind tunnel or field erodibility which were intermediate steps to the development of $E = f(I', K', C', L', V)$ as given in the Agr. Handbook. The functional relationship of $E = f(I', K', C', L', V)$ is nonanalytical in the sense that the expression cannot be solved simply by inserting values for the equivalent variables into the expression and turning the crank. Relations among some variables are complex and solution is obtained in a stepwise procedure involving graphical solutions with use of tables, chart with moveable scale and figures.

HORST: Is the soil loss accounted for in the wind erosion equation a net loss or only the outgoing flux?

SKIDMORE: The net soil loss from a field was used in converting from relative field erodibility to annual soil loss.