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A Wind Erosion Equation

N. P. Woodruff and F. H. Siddoway

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A Wind Erosion Equation[1]

N. P. Woodruff and F. H. Siddoway[2]

ABSTRACT

The amount of erosion, E, expressed in tons per acre per annum, that will occur from a given agricultural field can be expressed in terms of equivalent variables as: E = f(I′, K′, C′, L′, V) where I′ is a soil erodibility index, K′ is a soil ridge rougness factor, C′ is a climatic factor, L′ is field length along the prevailing wind erosion direction, and V is equivalent quantity of vegetative cover. The 5 equivalent variables are obtained by grouping some and converting others of the 11 primary variables now known to govern wind erodibility. Relations among variables are extremely complex. Charts and tables have been developed to permit graphical solutions of the equation. The equation is designed to serve the twofold purpose of providing a tool to (i) determine the potential erosion from a particular field, and (ii) determine what field conditions of soil cloddiness, roughness, vegetative cover, sheltering by barriers, or width and orientation of field are necessary to reduce potential erosion to a tolerable amount. Examples of these applications of the equation are presented. Weaknesses in the equation and areas needing further research are discussed.

The wind erosion equation was developed by the late Dr. W. S. Chepil. It is the result of nearly 30 years of research to determine the primary variables or factors that influence erosion of soil by wind.

The first wind erosion equation was a simple exponential expressing the amount of soil loss in a wind tunnel as a function of per cent soil cloddiness, amount of surface residue, and degree of surface roughness. The equation has been modified continually as new research data became available and now is a complex equation indicating the relation between potential soil loss from a field and some 11 individual primary field and climatic variables.

The equation is designed to serve the twofold purpose of determining (i) if a particular field is adequately protected from wind erosion, and (ii) the different field conditions of cloddiness, roughness, vegetative cover, sheltering from wind barriers, or width and orientation of field required to reduce potential soil loss to a tolerable amount under different climates.

This paper discusses the present status of the equation, points out some applications and uses of the equation, and indicates some weaknesses and areas needing further research.

PRIMARY WIND EROSION VARIABLES

The wind erodibility of land surfaces is governed by 11 primary variables. A brief description of each follows.

Soil Erodibility Index, I, and Knoll Erodibility, I_s

Soil erodibility, I, is the potential soil loss in tons per acre per annum from a *wide, unsheltered,* isolated field with a *bare, smooth,* noncursted surface. It has been developed from wind tunnel and field measures of erodibility and is based on climatic conditions for the vicinity of Garden City, Kans., during 1954–56 (4, 7, 8, 9, 10). It is related to soil cloddiness and its value increases as the percentage of soil fractions greater than 0.84 mm in diameter decreases. It can be determined by standard dry sieving procedure and use of Table 1.

Knoll erodibility, I_s, is a factor needed to compute erodibility for windward slopes less than about 500 feet long. It varies with slope and is expressed in terms of per cent slope, Fig. 1. The erosion rate for windward slopes longer than 500 feet is about the same as from level land; therefore, I_s is taken as 100% for this situation (13, 14).

Surface Crust Stability, F_s

The mechanical stability of the surface crust, F_s, if a crust is present, is of little consequence because it disintegrates readily due to abrasion after wind erosion has started.

Table 1—Soil erodibility I for soils with different percentages of nonerodible fractions as determined by standard dry sieving*

Percentage of dry soil fractions > 0.84 mm	Units									
	0	1	2	3	4	5	6	7	8	9
tens	tons/acre									
0	---	310	250	220	195	180	170	160	150	140
10	134	131	128	125	121	117	113	109	106	102
20	98	95	92	90	88	86	83	81	79	76
30	74	72	71	69	67	65	63	62	60	58
40	56	54	52	51	50	48	47	45	43	41
50	38	36	33	31	29	27	25	24	23	22
60	21	20	19	18	17	16	16	15	14	13
70	12	11	10	8	7	6	4	3	3	2
80	2	---	---	---	---	---	---	---	---	---

* For a fully crusted soil surface, regardless of soil texture, the erodibility I is, on the average, about 1/6 of that shown.

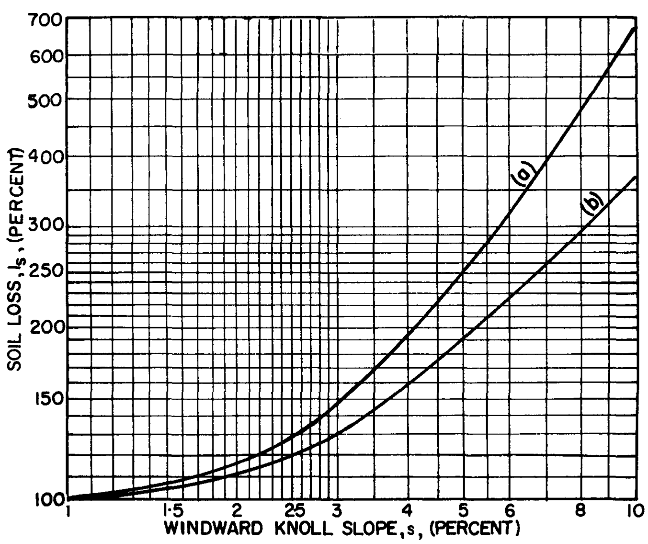

Fig. 1—Potential soil loss from knolls, expressed as per cent of that on level ground: (*a*) from top of knoll, (*b*) from that portion of windward slope where drag velocity and wind drag are the same as on top of knoll (from about the upper third of the slope).

[1] Contribution from the Soil and Water Conservation Research Division, ARS, USDA, and the Kansas Agr. Exp. Sta., Department of Agronomy Contribution no. 897. Received Jan. 6, 1965. Approved Mar. 30, 1965.

[2] Agricultural Engineer, USDA, Manhattan, Kan., and Soil Scientist, USDA, Sidney, Mont., respectively.

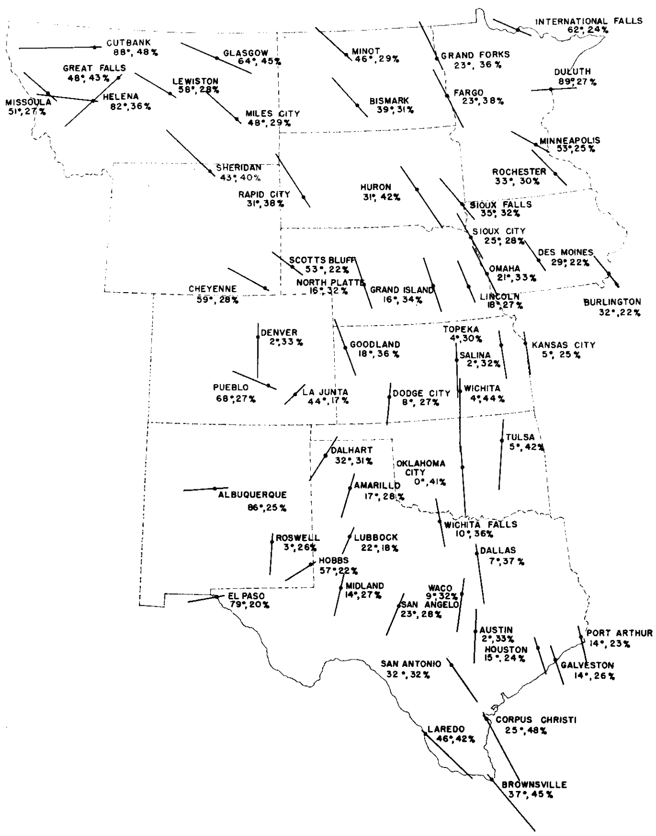

Fig. 2—Prevailing wind erosion directions in the Great Plains. Degrees indicate deviation of the prevailing wind erosion direction from north-south and percentages indicate per cent of erosion that occurs along that direction.

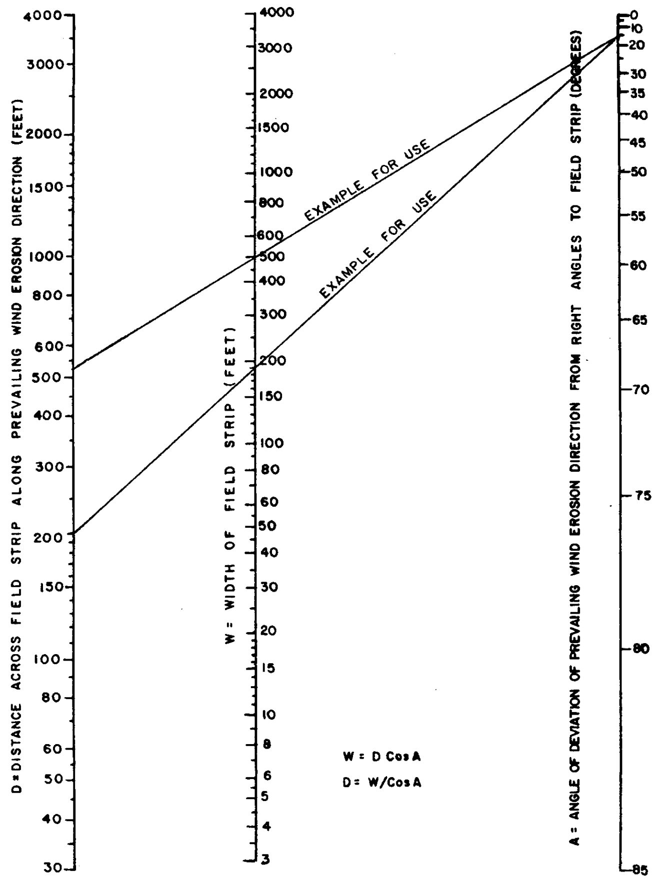

Fig. 3—Alignment chart to determine: (i) distance across field strip along the prevailing wind erosion direction from width of field strip and prevailing wind erosion direction, and (ii) width of field strip from prevailing wind erosion direction and distance across field strip along prevailing wind erosion direction.

It is also transitory and would be significant only where erodibility of a field at a given moment is considered. Where the average erodibility for the entire soil drifting period is being determined, which is usually the case, this condition should be disregarded.

Soil Ridge Roughness, K_r

K_r is a measure of soil surface roughness other than that caused by clods or vegetation, i.e., it is the natural or artificial roughness of the soil surface in the form of ridges or small undulations. It can be determined from a linear measure of surface roughness.

Velocity of Erosive Wind, v

The rate of soil movement varies directly as the cube of the wind velocity (2, 3, 17). Where average annual soil loss determinations are desired, the mean annual wind velocity corrected to a standard height of 30 feet is used. Atmospheric wind velocities are normally distributed; thus the higher the mean annual velocity the greater the probability of receiving high winds.

Soil Surface Moisture, M

The rate of soil movement varies approximately inversely as the square of effective surface soil moisture (5). Since detailed surface soil moisture is not generally available for different geographic locations, the wind erosion equation M is assumed to be proportional to the Thornthwaite P-E Index (15).

Distance Across Field, D_f

D_f is the total distance across a given field measured along the prevailing wind erosion direction. On an unprotected, eroding field the rate of soil flow is zero on the windward edge and increases with distance to leeward until, if the field is large enough, the flow reaches a maximum that a wind of a particular velocity can sustain. The distance required for soil flow to reach this maximum on a given soil is the same for any erosive winds. It varies only and inversely with erodibility of a field surface (11). It can be computed from width of field if prevailing wind erosion direction is known (6). Figure 2 provides data on prevailing wind erosion direction in the Great Plains (12). Similar maps giving this information for other geographc locations are being prepared. Figure 3 presents an alignment chart for determining the distance, D_f, along the wind direction for different widths of fields.

Sheltered Distance, D_b

D_b is the distance along the prevailing wind erosion direction that is sheltered by a barrier, if any, adjoining the field. Data on the effectiveness of different kinds of barriers in shielding the soil surface from erosion are meager but the distance is presently determined in a very general way by multiplying the height of the barrier by 10 (16).

Quantity of Vegetative Cover, R′

Surface residue amounts are determined by sampling, cleaning, drying, and weighing in accordance with Agricultural Research Service standardized procedure.[3] All quantities of vegetative residue, R′, connected with the wind erosion equation are based on washed, ovendry residue multiplied by 1.2 to make them comparable to the usual field measurements where samples are drycleaned and air-dried.

Kind of Vegetative Cover, S

S is a factor denoting the total cross-sectional area of the vegetative material. The finer the material and the greater its surface area, the more it reduces the wind velocity and the more it reduces wind erosion.

Assigned values of S for different kinds of vegetative material so far investigated are:

Small grain stubble and stover	1.00
Sorghum stubble and stover	.25
Corn stubble and stover	.20
Small grain in seedling and stooling stage, dead or alive	2.50

Orientation or Vegetative Cover Variable, K_0

K_0 is in effect the vegetative surface roughness variable. The more erect the vegetative matter, the higher it stands above the ground, the more it slows the wind velocity near the ground, and the lower is the rate of soil erosion. K_0 includes the influence of distribution and location of vegetation such as width and direction of rows, uniformity of distribution, and whether the vegetation is in a furrow or on a ridge. K_0 has been assigned a value of 1.0 for absolutely flat, small grain stubble with straw aligned parallel with wind direction on smooth ground in rows 10 inches apart at right angles to wind direction. For other orientations and other residues, K_0 varies as a power function of amount of residue, R′, for values of R′ greater than 1,000 lb/acre. The exponent ranges from approximately 0.5 for flattened small grain or sorghum to 0.25 for standing small grain and 20-inch-high sorghum. In the equation the variable, K_0, is combined with variables S and R′ and expressed in terms of an equivalent vegetative factor which is discussed in a subsequent section of this paper.

[3] Committee Report, July 1962. A standardized procedure for residue sampling. ARS 41–68. 10 p.

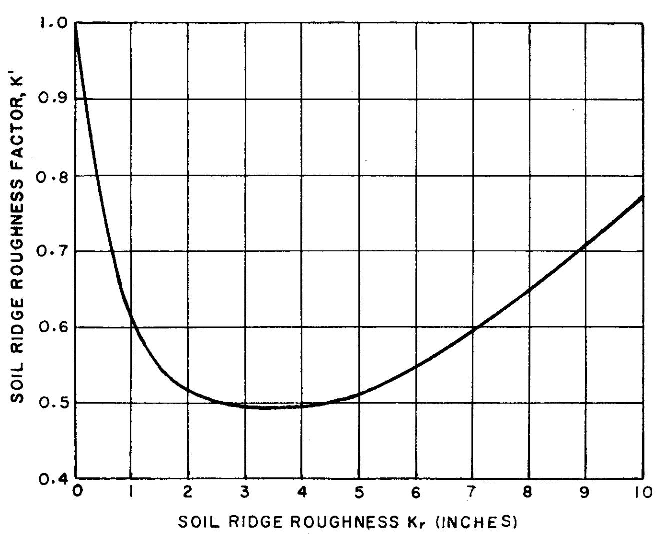

Fig. 4—Chart to determine soil ridge roughness factor K′ from the soil ridge roughness K_r.

EQUIVALENT WIND EROSION VARIABLES

Because of the nature of the relationship between soil erodibility, E, and some of the 11 primary variables, it has been found convenient to disregard some variables, group some, and convert others to equivalents as follows:

Soil erodibility, I Knoll erodibility, I_s	Soil and knoll erodibility, I′
Surface crust stability, F_s	Disregard, crust transient
Soil ridge roughness, K_r	Soil ridge roughness factor, K′
Wind velocity, v Surface soil moisture, M	Local wind erosion climatic factor, C′
Distance across field, D_f Sheltered distance, D_b	Field length, L′
Quantity of vegetative cover, R′ Kind of vegetative cover, S Orientation of vegetative cover, K_0	Equivalent quantity of vegetative cover, V

Soil and knoll erodibility, I′, is obtained simply by multiplying soil erodibility, I, (Table 1) by knoll erodibility, I_s, (Fig. 1) if a knoll or hill is involved. For level land or slopes longer than 500 feet, I_s is equal to 100%; therefore, I = I′.

The soil ridge roughness factor, K′, is expressed in terms of height of standard soil ridges spaced at right

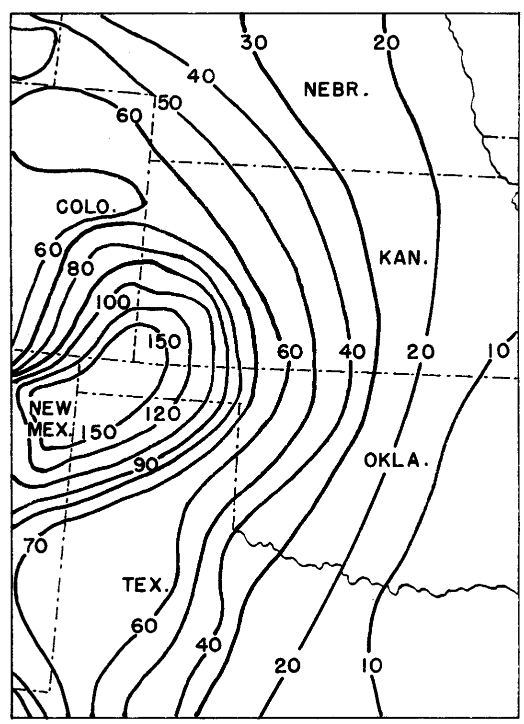

Fig. 5—Wind erosion climatic factor C′ (per cent) for Kansas and parts of Nebraska, Colorado, Oklahoma, New Mexico, and Texas. Similar maps for other parts of the USA are available from the Erosion Research Laboratory at Manhattan, Kans.

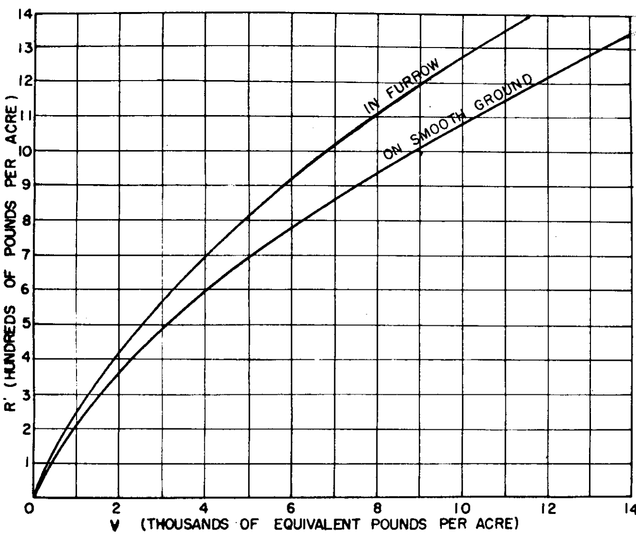

Fig. 6—Chart to determine V from R′ or R′ from V of live or dead small grain crops in seedling and stooling stage, above the surface of the ground, for crop in 3-inch-deep furrow (as created by a deep furrow drill) and on smooth ground.

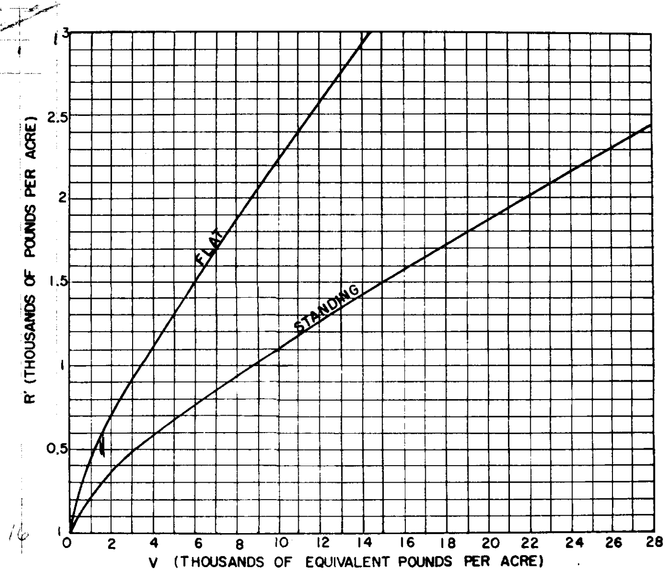

Fig. 7—Chart to determine V from R′ or R′ from V of standing and flat anchored small grain stubble with any row width up to 10 inches, including stover.

angles to the wind and with a height-spacing ratio of 1:4 (18). The rate of soil flow varies with ridge height, degree of cloddiness of ridges, and wind velocity (1). The relationship between soil flow and ridge height, within prescribed limits, follows an approximate catenary curve. Ridges 2 to 4 inches high are most effective in controlling erosion. Rate of flow increases with ridges greater than 4 inches or less than 2 inches high. Figure 4 presents a curve for obtaining the equivalent soil ridge roughness factor, K′, from a measure of K_r. The curve is based on a design velocity of 50 miles/hour at 50-foot height with wind direction at 45 degress to the ridges.

The local wind erosion climatic factor, C′, has been developed from the relationship stating that rate of soil flow varies directly as the cube of the wind velocity and inversely as the square of the effective moisture or for reasons stated previously, the P-E index. The climatic factor was computed from the equation

$$C' = 34.483 \frac{v^3}{(\text{P-E})^2} \qquad [1]$$

where v = mean annual wind velocity for a particular geographic location corrected to a standard height of 30 feet and P-E = Thornthwaite's P-E ratio = $10(P/E) = 115(P/T - 10)^{1.111}$. Factor C′ has been computed for many locations throughout the USA. A map giving general ranges of values of C′ for the western half of the USA will be found in a previous publication (10). Detailed maps have also been prepared and are available from the Erosion Research Laboratory at Manhattan, Kans. Figure 5 is such a map for the center of the "dust bowl" area of the 1930's.

The equivalent field length, L′, is the unsheltered distance across the field along the prevailing wind erosion direction, thus $L' = D_f - D_b$.

The equivalent vegetative cover variable, V, is obtained by multiplying the variables R′, S, and $K_o = f(R')$ together. Values of V have been computed for various kinds and amounts of residue and are presented in Fig. 6, 7, and 8.

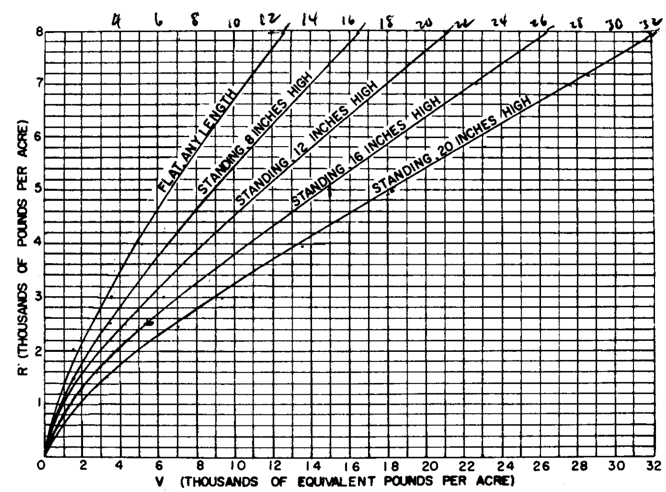

Fig. 8—Chart to determine V from R′ or R′ from V of standing and flat grain sorghum stubble of average stalk thickness, leafiness, and quantity of tops on the ground.

RELATIONSHIPS BETWEEN VARIABLES

The general functional relationship between the dependent variable, E, the potential average annual soil loss in tons per acre per annum, and the equivalent variables may be expressed as

$$E = f(I', C', K', L', V). \qquad [2]$$

Mathematical relationships have been established between individual variables. However, because of the complexity of these relations, e.g., the relation between E and V is an exponential equation of the form $E = f(e^V)$ while that between E and L′ is a power equation of the form $E = f(L' - b)^n$, a single equation expressing E as a function of the 5 dependent variables has not yet been derived. The equation can be solved in the following 5 steps, the latter 2 involving graphical solutions, with each step evaluating the effect of an additional variable.

Step 1—Determine erodibility $E_1 = I'$ that would occur from a wide, isolated, smooth, unsheltered, bare field having a determined percentage of dry aggregates greater than 0.84 mm in diameter and located under climatic conditions as at Garden City, Kans.

Step 2—Account for effect of roughness, K', and find erodibility $E_2 = I' \times K'$.

Step 3—Account for effect of local wind velocity and surface soil moisture, C', and find erodibility $E_3 = I' \times K' \times C'$.

Step 4—Account for effect of length of field, L', and determine $E_4 = I' \times K' \times C' \times f(L')$. Determination of E_4 is not a simple multiplication because L', $I'K'C'$, and $I'K'$ are all interrelated. A graphical solution of this portion of the equation is given in Fig. 9.

Step 5—Account for effect of vegetative cover, V', and determine the actual annual erosion for a specific field, $E_5 = E = I' \times K' \times C' \times f(L') \times f(V')$. Here again the relationships among E_4, V', and E are not simple. A graphical solution is given in Fig. 10.

In considering the significance of the value of E, the potential annual erosion determined in these 5 steps, it is important to recall that the first step was to determine the erodibility of a wide, bare, smooth field having a certain cloddiness as if it were located at Garden City, Kans., during 1954–56 when there were 38 seasonal, (January 1 to April 30) severe duststorms and 61 annual storms. The next 4 steps then adjust this erodibility in accordance with specific roughness, climatic, field length, and vegetative cover conditions. Thus, even though average annual values of certain factors such as wind velocity may be used in the computations, the equation actually evaluates the erodibility of a field having certain L', K', and V values in terms of what it would have been during severe soil blowing time. Therefore, when the equation is used to design erosion control measures, as is done in subsequent sections of this paper, the design is based on actual erosive condition, not averages.

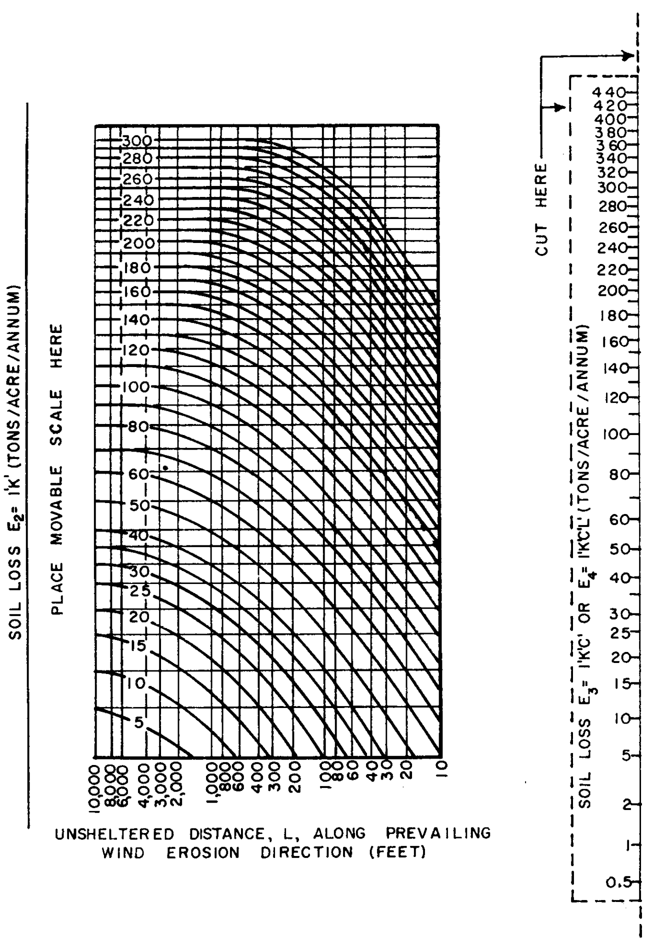

Fig. 9—Chart to determine soil loss $E_4 = I'K'C'L'$ from soil loss $E_2 = I'K'$ and $E_3 = I'K'C'$ and from unsheltered distance L' across the field.

APPLICATIONS OF THE EQUATION

The wind erosion equation can be used to estimate the potential average annual soil loss, E, or solved in reverse to determine the condition of any one of I', K', L', or V needed to control erosion. The only conditions that cannot be controlled are those associated with the climatic variable, C'. Examples of use of the equation follow to (i) determine potential average annual soil loss, E, (ii) determine vegetative cover needed to control erosion at a tolerable level, and (iii) determine width of strips needed to control erosion at a tolerable level.

Determining Potential Average Annual Soil Loss, E

A. Conditions

Assume a large field with a 2,640-foot north-south width, mostly flat but with a significant knoll with an average windward slope of 3% located in the vicinity of Pratt, Kans. The field has 800 lb/acre of cleaned, air-dry, flat wheat stubble. Dry sieving indicated 25% of soil fractions were >0.84 mm in diameter. There is a 60-foot-high shelterbelt on the south side of the field. There are no ridges, so soil ridge roughness equals zero.

B. Steps to Determine E

1) Determine $E_1 = I'$. Use Table 1: I= 86 tons/acre per annum.

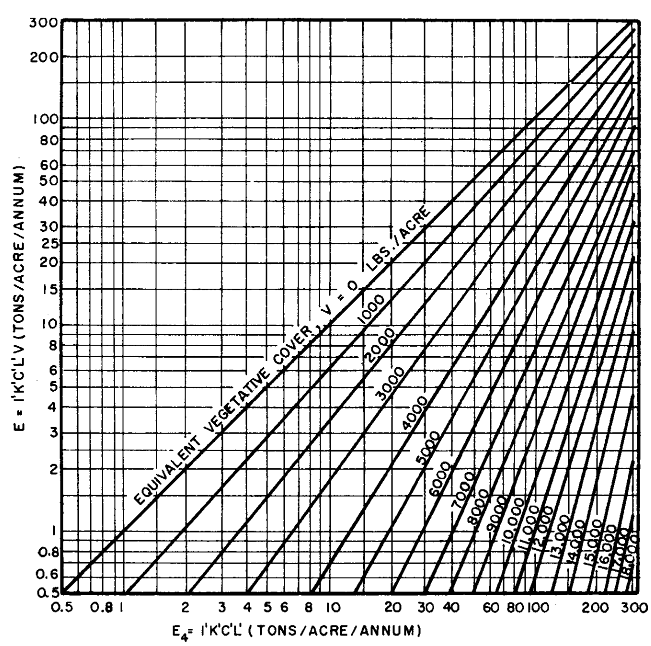

Fig. 10—Chart to determine soil loss $E = I'K'C'L'V$ from soil loss $E_4 = I'K'C'L'$ and from the vegetative cover factor, V. The chart can be used in reverse to determine V needed to reduce soil loss to any degree.

Use Fig. 1 to determine I_s. $I_s = 145\%$ for top of knoll, 130% for windward slope, and 100% for rest of field. To be safe, use 145%; therefore, $E_1 = I \times I_s = 86 \times 1.45 = 125$ tons/acre per annum.

2) Determine $E_2 = I'K'$. Use Fig. 4 to determine K'. $K' = 1.0$. $E_2 = 125 \times 1 = 125$ tons/acre per annum.
3) Determine $E_3 = I'K'C'$. Use Fig. 5 to determine C'. $C' = 50\%$ for vicinity of Pratt, Kansas. $E_3 = 125 \times 1 \times .50 = 62.5$ tons/acre per annum.
4) Determine $E_4 = I', K', C', f(L')$
   a) Determine prevailing wind erosion direction from Fig. 2. Map shows 8° deviation from N-S direction for Dodge City and 4° deviation for Wichita; therefore, Pratt would have about 6° deviation west of south.
   b) Determine distance D_f from Fig. 3. $D_f = 2{,}750$ feet.
   c) Determine L' by subtracting D_b. D_b, as stated earlier, equals 10 times the height of the barrier or $10 \times 60 = 600$ feet. $L' = D_f - D_b = 2{,}750 - 600 = 2{,}150$ feet.
   d) Use Fig. 9 to obtain $E_4 = I', K', C', f(L')$. Cut out movable $E_3 = I'K'C'$ scale. Place it along $E_2 = I'K'$ ordinate so that 62.5 on movable scale coincides with 125 on ordinate. Move to right, down along curved 125 line to intersection of $L' = 2{,}150$ feet, then move horizontally left to movable E_3 scale and read $E_4 = I', K', C', f(L') = 60$ tons/acre per annum.
5) Determine $E_5 = E = I', K', C', f(L'), f(V)$
   a) Determine V from Fig. 7. $V = 2{,}500$ equivalent lb/acre.
   b) Use Fig. 10 to determine $E_5 = E$. Start with $E_4 = 60$ on abscissa of Fig. 10. Move vertically upward to intersection of $V = 2{,}500$, then move horizontally to left to ordinate, E. $E = 25$ tons/acre.

If the knoll had not been on the field, E_1 would have equalled 86 instead of 125 and the equation would give a final erodibility, E, of 15 tons/acre per annum. Thus erodibility, although quite high on the entire field, was substantially greater when evaluated for the knoll condition.

Determining Vegetative Cover, R′, Needed to Control Erosion at a Tolerable Level

A. Conditions

$E_1 = I' = 86$ tons/acre per annum ($I = 86$ and I_s with no knolls $= 100\%$)
$K' = 1.0$ ($K_r = 0$)
$C' = 50\%$
$L' = 2{,}200$ feet (prevailing wind direction from south and no barriers)
$S =$ small grain stubble
$K_o =$ flat
$E =$ tolerable soil loss $= 5$ tons/acre per annum. (What constitutes a tolerable loss varies with kind of crop, economic choice, and soil reserves. Five tons per acre is more or less a judgement value based on present knowledge of erosive effects.)

B. Steps to Determine R′

1) Determine $E_2 = 86 \times 1.0 = 86$ tons/acre per annum.
2) Determine $E_3 = 86 \times 1.0 \times .5 = 43$ tons/acre per annum.
3) Determine E_4 from Fig. 9. $E_4 = 40$ tons/acre per annum.
4) Determine V using Fig. 10 and a tolerable E of 5 tons/acre per annum. Enter ordinate E of Fig. 10 at 5. Proceed horizontally to intersection of $E_4 = 40$ and read $V = 4{,}500$ equivalent lb/acre.
5) Determine R′ needed by using Fig. 7 (flat small grain stubble). $R' = 1{,}200$ lb/acre which is the amount required to reduce the erosion to a 5-ton/acre per annum level.

Determining Width of Strips Needed to Control Erosion

A. Conditions

Assume same field conditions as previous example except that it is decided that it would be possible to maintain only 800 lb/acre of vegetative cover and it was decided to use a combination of this vegetative cover and field strips to control erosion. The problem, therefore, is to determine required width of strips, L′, needed to reduce soil loss to 5 tons/acre per annum.

B. Steps to Determine L′

1) Determine $E_2 = 86 \times 1.0 = 86$ tons/acre per annum.
2) Determine $E_3 = 86 \times 1.0 \times .5 = 43$ tons/acre per annum.
3) Determine V from Fig. 7. $V = 2{,}500$ equivalent lb/acre.
4) Determine E_4 from Fig. 10 for a tolerable E of 5 tons/acre per annum. Enter ordinate E at 5, proceed horizontally to right to $V = 2{,}500$, then move vertically downward to $E_4 = 18$ tons/acre per annum.
5) Determine L′ from Fig. 9. Place $E_3 = 43$ on movable scale so it coincides with $E_2 = 86$. Find $E_4 = 18$ on movable scale and from this point move horizontally to right to intersection of curved line coming down from point (43, 86), then proceed vertically downward to $L' = 150$ feet.

The wind erosion equation can be used to consider other possible conditions or combinations of conditions that could be used to most effectively control erosion. The preceding examples serve only to illustrate possible applications.

NEEDED RESEARCH

The general framework of the wind erosion equation has been developed but many details are still lacking. Further research is needed to more thoroughly evaluate some of the primary variables that influence wind erosion —especially the interacting influence of combinations of these variables.

More information is needed on the influence of different implements on soil cloddiness, soil ridge roughness, and vegetative cover. This information would be important in prescribing effective methods of tillage to control erosion.

Information is needed on the average distance, D_b, of full and partial protection from wind erosion afforded by barriers of various widths and spacings in various geographic locations and for various soils.

Prevailing wind erosion direction needs to be determined for areas outside of the Great Plains.

Better information on surface soil moisture in relation to climatic conditions is also needed to improve the reliability of the climatic factor, C′. The Thornthwaite Index can be considered only as a rough estimate of moisture conditions. Climatic factor, C′, also should be computed on a monthly or seasonal basis to permit better evaluation of short-time, highly erosive periods.

Seasonal and annual soil erodibility, I, based on dry sieving, needs to be determined for various soil types wherever wind erosion is a problem.

Information is also needed on values of vegetative cover factor, S, and orientation, K_o, for crops other than those already investigated.

Further information on any one or all of these factors will help to eliminate weaknesses and increase the accuracy and usefulness of the wind erosion equation.

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