

# A Simulation Model of Daily Wind Erosion Soil Loss

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## ABSTRACT

EPIC's (Erosion Productivity Impact Calculator) wind erosion submodel is described in terms of the equations and concepts needed for interfacing the wind erosion equation with EPIC. The required equations are presented following an analysis of the wind erosion equation literature which shows how the wind erosion equation was developed from short-term data. This analysis is based on viewing the soil loss as a time and space integration of a surface soil flux. The wind erosion equation is then partitioned into those parts that represent the short-term effects and the integration process. From this it is seen how one might ideally modify the wind erosion equation. The analyses point the way for future improvements in soil loss prediction equations. The results of the five 50-yr simulations are also presented.

## INTRODUCTION

The objective of the study considered here is the adaptation of the wind erosion equation (Woodruff and Siddoway, 1965; Skidmore and Woodruff, 1968; Skidmore, 1976), which predicts annual average soil loss for a single crop, for use in the erosion productivity impact calculator (EPIC) (Williams et al., 1982). EPIC, which simulates the long-term effects of soil loss due to wind and water erosion, computes at a daily rate and considers multiple crops per year. The wind erosion equation, therefore, needs changes to allow adaptation of soil loss expressed in tons/(acre-year) to metric tonnes/(hectare-day) and inclusion of a method to simultaneously handle a growing crop and residues from previous crops. Of particular significance is the required time transformation from a 1-yr average to a 1-day average.

In the following sections, the basic structure of the wind erosion equation is reviewed as an aid to comprehending the methods used in adapting the equation for use in EPIC. The methods are then discussed, followed by a brief description of the implementation. Finally, some numerical results from a typical EPIC simulation run are analyzed for reasonableness.

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## WIND EROSION EQUATION

### General Concepts

The wind erosion equation was originally developed as a prediction and design tool to allow estimation of soil loss and the effect of various conservation practices in reducing soil loss. Consequently, the units of measurement were chosen to be easily grasped. For example, since soil loss is cyclic with a yearly period, the year was a natural choice.

The variable chosen to express soil loss, E, has the units of a soil loss flux. However, since it is defined as a potential average annual soil loss (Woodruff and Siddoway, 1965), E represents the temporal and spatial average of f, the "point" flux. E cannot vary in the time interval of 1 yr or over the space of a given field. It can only vary due to different levels of its five factors: I, K, C, L, and V. (All symbols are defined in Table 1). Actually, these factors are functions of other variables.

Since E is an average flux in space and time, then for an erodible field of area A for time duration T we have

$$m = \int_T \int_A f(x,y,t) dx dy dt \dots \dots \dots [1a]$$

and finally

$$E = m/(AT) \dots \dots \dots [1b]$$

(The geometry for a rectangular field of area A, (A = lw), is depicted in Fig. 1.) It should be noted from equation [1a] that the shape of the area over which the averaging is performed is contained in the limits of

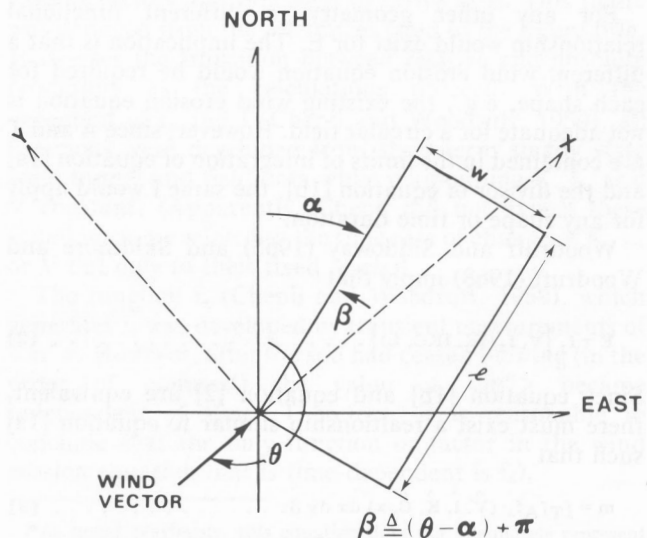


Fig. 1—A plan view of a rectangular field, relative to north, showing the defining angles and the wind reference coordinate system (x, y).

TABLE 1. NOTATION. M, L, AND T REFER TO THE DIMENSIONS OF MASS, LENGTH, AND TIME.

| Symbol    | Definition and dimensions  | Symbol                                | Definition and dimensions   |
|-----------|--|---------------------------------------|---|
| A         | area of the erodible field, $L^2$ , or the angle between $w$ and the positive $x$ axis, dimensionless              | T                                     | time interval, on the order of 1 year, T  |
| $A_3$     | top surface of a control volume for the soil loss system, $L^2$  | t                                     | time, T, or metric tonnes, M  |
| a         | defined below equation [7], dimensions unknown   | u                                     | wind velocity, $L/T$  |
| b         | defined below equation [7], dimensions unknown   | $u_e$                                 | erosive wind velocity, $L/T$  |
| C         | climatic factor, dimensionless   | $u_t$                                 | threshold velocity, the wind velocity below which no soil moves, $L/T$  |
| c         | parameter for function $p$ , $L/T$   | V                                     | equivalent quantity of vegetative cover, $M/L^2$  |
| $c_1$     | a constant   | W                                     | work done in moving soil, $M L^2 T^{-2}$  |
| E         | potential average annual soil loss, $M L^{-2} T^{-1}$  | w                                     | small dimension of a rectangular field, L   |
| $E_2$     | product of I and K, $M L^{-2} T^{-1}$  | WEE                                   | wind erosion equation   |
| $E_3$     | product of I, K, and C, $M L^{-2} T^{-1}$  | X                                     | relative field erodibility as defined in Chepil (1960), dimensionless   |
| $E_4$     | $E_3$ modified by L, $M L^{-2} T^{-1}$   | x                                     | distance along the field in the direction of the wind, L  |
| $E_5$     | E or alternative of $E_4$ modified by V, $M L^{-2} T^{-1}$   | Y                                     | annual soil loss, as defined in Chepil (1960), $M/L^2$  |
| EPIC      | acronym for erosion productivity impact calculator, the USDA soil loss-soil productivity simulator                 | y                                     | distance perpendicular to $x$ and $z$ , L   |
| $e_i$     | erosive wind energy for the $i$ -th period, $M L^2 T^{-2}$   | z                                     | distance perpendicular to $x$ and $y$ , L   |
| f         | the normal component of the net soil flux vector along the ground surface, $M L^{-2} T^{-1}$                       | $\alpha$                              | the field angle relative to north, clockwise positive, dimensionless  |
| $f_i$     | a function; $i$ is an integer subscript used to differentiate between functions. Most $f_i$ are defined in Fig. 2. | $\beta$                               | the field angle relative to the wind, counterclockwise positive from the positive $x$ axis, dimensionless   |
| I         | soil erodibility, $M L^{-2} T^{-1}$  | $\Delta$                              | difference operator, dimensionless  |
| K         | soil ridge roughness, dimensionless  | $\theta$                              | the direction of the wind vector relative to north, clockwise positive, dimensionless   |
| k         | $k$ -th value of an index or parameter for function $p$ , dimensionless  | $\tau_{zx}$                           | shear stress on $z$ plane in $x$ direction, $M L^{-1} T^{-2}$   |
| L         | field length, a function, see equation [7], L  | <b>Subscripts</b>                     |   |
| $l$       | large dimension of a rectangular field, L  | i                                     | index   |
| m         | soil loss, M   | k                                     | $k$ -th value of an index   |
| $\dot{m}$ | mass flow rate of soil through a prescribed surface, $M/T$   | m                                     | mixture   |
| $m''$     | soil loss per unit area, $M/L^2$   | n                                     | upper limit of index, dimensions vary   |
| n         | upper limit of an index, dimensions vary   | r                                     | reference   |
| P         | power into soil loss system, $M L^2 T^{-3}$  | t                                     | total   |
| $P_i$     | proportion of $R_i$ in mixture, dimensionless  | <b>Superscripts and other symbols</b> |   |
| p         | a Weibull probability density function, $T/L$  | $\wedge$                              | caret variable is time and or space dependent   |
| Q         | energy loss from soil loss system as heat, $M L^2 T^{-2}$  | $\sim$                                | implies that the variable is a form of relative erodibility   |
| q         | integral of $f$ along $x$ within the limits of the field, $M L^{-1} T^{-1}$  | $\cdot$                               | implies variable is a time rate of change   |
| $R$       | biomass (surface) density, dry weight of vegetative cover per unit area, $M/L^2$                                   | $\langle \rangle_{\Delta x}$          | an average of the function within the brackets with respect to an interval which is shown here as $\Delta x$ . If the interval is unambiguous, it is omitted. |
| $r_i$     | erosive wind energy factor for the $i$ -th period, dimensionless   | $\hat{=}$                             | defined   |
| S         | small grain equivalent, small grain biomass surface density, $M/L^2$   |                                       |   |

integration, whereas the numerical value for A is contained in the denominator of the function, i.e., equation [1b]. Consequently, any equation that purports to compute an average flux must have the geometry implied. By analogy, the time interval is also implied. Also, because of these implications, there should be no time or space varying "variables" in the integrated or average flux equation. Only parameters can exist, e.g.,  $l$ ,  $w$ , T, or perhaps the parameters of a probability distribution function of the wind vector.

For any other geometry, a different functional relationship would exist for E. The implication is that a different wind erosion equation would be required for each shape, e.g., the existing wind erosion equation is not adequate for a circular field. However, since A and T are contained in the limits of integration of equation [1a] and the divisor of equation [1b], the same f would apply for any shape or time duration.

Woodruff and Siddoway (1965) and Skidmore and Woodruff (1968) imply that

$$E = f_2 \left\{ V, f_3(IK, IKC, L) \right\} \dots \dots \dots [2]$$

Since equation [1b] and equation [2] are equivalent, there must exist a relationship similar to equation [1a] such that

$$m = \int_{T/A} f_4(\hat{V}, \hat{I}, \hat{K}, \hat{C}, x) dx dy dt \dots \dots \dots [3]$$

where all or some of the independent variables are functions of space and/or time. The use of the caret on

the factors implies that if an independent variable is present in equation [2], then some unknown functional form must exist at the flux level, i.e.,  $f_4$ , for each factor. This functional form could be identical to the uncared variable if the factor was independent of time and space, or almost so, in the sense that it would vary only slightly.

Although  $f_4$  is unknown, it is instructive to analyze the structure of equation [2], utilizing the underlying concept of a flux function, i.e.,  $f_4$ . Perhaps one could then determine which factors (really functions) might be treated as independent of the 1-yr time duration implied in E and hence applicable to the 1-day time step computations of EPIC.

A second problem, which is not unique to the EPIC application, can also be evaluated by this analysis. That is, how does one estimate L as used in equation [2] when it is observed that L depends on the period of averaging? Chepil et al. (1964) addressed this problem, with the resulting solution being modified by Skidmore (1965). For use in EPIC, the concept of L has to be further modified to allow for the daily time interval, yet allow for spatial averaging of some function related to L. This is essentially the spatial analog of the time step problem. Both problems will be analyzed in the following two sections.

**Time Scale Analysis**

Review of early wind erosion literature (Chepil and Woodruff, 1954, 1959; Chepil, 1959) indicates that most of the data that was used in the development of the wind erosion equation was based on wind tunnel studies. The

duration of time for which the soil mass was collected was in the order of minutes and the area was between 0.8 to 8 m<sup>2</sup>. In fact, as Chepil (1959, page 214) indicated, the measurements in the wind tunnel were of such short duration, due to the limited amount of erodible soil in the sample trays, that the soil flow rate could not be measured. Instead, the mass of soil lost per unit area  $\langle m'' \rangle_{\Delta A}$  was measured and used in computing  $\bar{I}$ , the measure of relative erodibility.

One problem in interpreting early forms of the wind erosion equation is that the term "erodibility" has been used in defining both relative and absolute measures of soil loss. Erodiability was dimensional (tons/acre) in Chepil and Woodruff (1959), dimensionless in Chepil (1959), and finally in Chepil (1962) and ever since, dimensional (tons/(acre·yr)). The conversion from relative soil loss (dimensionless) to flux units was accomplished by a graph discussed by Chepil (1960) where he related a calculated relative field erodibility to a measured soil loss for 69 fields for three replicates of a 4-month period. (He also presented an equation which, by today's standards, is not an accurate representation of the graph.) The calculated values of relative field erodibility were based on the methods outlined in Chepil (1959). The conversion graph, plotted as Fig. 1, page 144 (Chepil, 1960), represents Chepil's method of relating short-term (minutes) soil loss data, i.e.,  $q$  (Chepil, 1946) and  $\langle m'' \rangle_{\Delta A}$  (Chepil and Woodruff, 1959) to  $E$ , which spans a 12-month period and areas that are wide and long compared to a wind tunnel. Hence, we have an equation or graph that accomplishes a change in time and length scales and a change from relative to absolute soil loss. Chepil's conversion equation performs the equivalent of averaging the flux  $f$  in  $y$  and  $t$  and completes the averaging in  $x$ . This can be expressed analytically in terms of  $q$  as

$$E = \frac{1}{AT} \int_T \int_y q \, dy \, dt \dots \dots \dots [4]$$

where

$$q \hat{=} \int f \, dx \dots \dots \dots [5]$$

where

- A = the area considered and
- T = 4 months.

The basic data for the conversion equation while representing a 4-month time interval was scaled to 1 yr by using the occurrence rate of varying intensity dust storms as a weight factor. Since equation [4] is analogous to Chepil's conversion equation, it can therefore be concluded that relative field erodibility is related to  $q$ .

This conversion equation was later modified by a factor of 1/3 (Chepil et al., 1962, page 165) because the climatic factor estimates for Garden City, Kansas during the 3-yr data collection period were 2.5 times greater than the 40-yr average (40 replicates) for which the C factor is defined. Additional unknown considerations caused the 2.5 to become 3. The final form of the conversion equation was that given in Chepil (1960) with the 1/3 factor, i.e.,

$$Y = (1/3) \left\{ 140 X^{0.287} - 1 / (0.01525 \cdot 1.065^X) \right\} * \dots \dots \dots [6]$$

The first documented application of the original conversion data was that of Niles (1961). Niles used the factors for computing relative erodibility in a manner similar to Chepil (1959), except that it was converted to an absolute value via the use of Table 3 of Chepil (1960) as a final step. This application was contrasted with Chepil (1962) where the concept of relative erodibility was totally suppressed and was replaced with absolute values throughout the calculation procedure.

Chepil evidently felt that equation [6] or its tabulated representation (Chepil, 1960, page 144) scaled by 1/3 was adequate to transfer any relative erodibility, e.g., relative soil erodibility, relative surface erodibility, and relative field erodibility (Chepil, 1959, page 215) to an absolute amount. Consequently, he developed a new soil erodibility table which related  $\bar{I}$  in absolute units to aggregate size (Chepil, 1962, Table 1). Approximate numerical values of the table can be generated by applying equation [6] to Table 2 of Chepil and Woodruff (1959). Skidmore (1976) first noted this particular use of the conversion equation.

A more accurate method of determining  $\bar{I}$  used the vertical scales of Fig. 5 of Chepil (1962). The numerical values of the relative and absolute erodibility were plotted on the vertical axis for the  $V$  factor equation. (It appears that Chepil modified his initial conversion graph (or equation) in order to develop this new function implied by the axis. We designate this new function as  $f_6$ .)

It is significant that Fig. 5 of Chepil (1962) depicted equation [6] in conjunction with an equation relating  $V$  to the relative soil erodibility. This was the second application of  $f_6$  to convert a relative erodibility to an absolute amount. In fact, perusal of Figs. 3 and 4 (Chepil, 1962), which were related to the effect of soil ridge roughness and  $L$  on absolute erodibility, shows the same vertical scale as his Fig. 5.

From this it can be seen that Chepil has taken the functions of  $\bar{I}$ ,  $K$ ,  $L$ , and  $V$  in their relative forms and via  $f_6$  related them to absolute values. He obviously believed that the function could be applied to various kinds of erodibility to allow use of the relative factor equations for absolute values!

Fig. 2 illustrates the sequence of calculations using the various factors and functions to arrive at  $E$ . This figure was deduced from the references cited in the figure title. It stresses the transition between relative and absolute erodibility as the calculations proceed. With the exception of  $f_6$  and  $\bar{I}$  (Chepil and Woodruff, 1959), all functions were developed from short-term steady state wind tunnel and field data while maintaining  $K$ ,  $L$ , and  $V$  constant. (Apparently, Chepil did not expect these functions to be related to the time rate of change of  $K$ ,  $L$ , or  $V$  but only to their fixed levels.)

The function  $f_5$  (Chepil and Woodruff, 1959), which generates  $\bar{I}$ , was developed by transient measurements of  $\langle m'' \rangle$ . However, after the soil had ceased blowing (in the order of minutes!) the value of  $\langle m'' \rangle$  became independent of time. Therefore, it is reasonable to conclude that the only function or factor in the wind erosion equation that is time-dependent is  $f_6$ .

\*As noted previously, this equation does not adequately represent the graph and is not recommended for calculation purposes. It is used here for reference only. As noted later, Chepil used a modification to equation [6] to develop Fig. 5 of Chepil (1962).

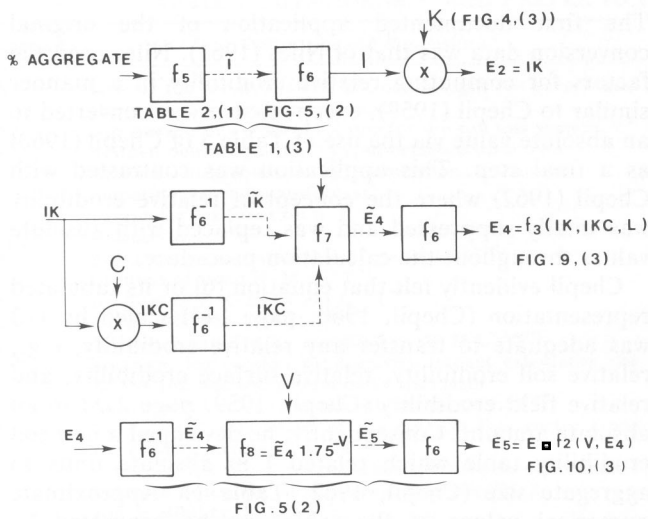


Fig. 2—Flow of the wind erosion equation depicting the functional relationships between relative erodibility (---) and absolute (—). Parenthetical numbers refer to the following citations: (1) Chepil and Woodruff (1959), (2) Chepil (1962), (3) Woodruff and Siddoway (1965).

It should not be implied that  $K$ ,  $L$ , and  $V$  cannot change with time for use in the wind erosion equation in its relative form, i.e.,  $f_5$ ,  $f_7$ , and  $f_8$ . However,  $K$ ,  $L$ , and  $V$  cannot be allowed to change in the absolute form of the equation, i.e., the present wind erosion equation, due to  $f_6$ . Of course, one could argue that during the collection of data for developing  $f_6$ ,  $K$ ,  $L$ ,  $V$ , and  $\bar{I}$  were changing to some degree and hence some single values must have been used. Chepil (1960) does not make this clear, but Woodruff and Siddoway (1965, page 606) imply that the selection of values for  $K$ ,  $L$ , and  $V$  should be based on a specific time interval called the "severe blowing time." At any rate, considering the methods used in developing the subfunctions, changing values of  $K$ ,  $L$ , and  $V$  would appear legitimate for short-term usage with the wind erosion equation, provided that a new  $f_6$  could be developed.

### Length Scale Analysis

Integration of  $f_4$  (equation [3]) and division by  $A$  and  $T$  results in equation [2], the wind erosion equation. As noted earlier, this averaging process must result in a wind erosion equation whose independent variables are parameters, such as the  $l$  or  $w$ , that do not vary over  $A$  or during  $T$ . Consequently,  $L$  in equation [2] cannot vary in time or space. It must represent a function that influences  $E$  because: (a)  $q$  varies with  $\Delta x$ , the distance downwind bounded by the field geometry, (b)  $\Delta x$  varies with the field geometry and  $\beta$ , and (c) the limits of integration for  $q$  with respect to  $y$  also depend on the field geometry and  $\beta$ . Because  $\beta$  varies with time due to the wind angle changing (Fig. 1),  $L$  then is a function that must vary with the field geometry parameters and some wind angle parameters, e.g.,

$$L = L(l, w, \alpha, a, b) \dots \dots \dots [7]$$

The parameters  $a$  and  $b$  result from characterizing the wind angle as a random variable in time whose yearly probability density function might have a two parameter distribution. These parameters would depend on the location of the field site.

In the previous section it was argued that  $f_7$  (Fig. 2), which has  $L$  as its input, was developed from short-term data and hence could accept a time-varying input. Perhaps it would be better to replace  $L$  in Fig. 2 with  $\Delta x$ , the distance down the field, which can change with time, since  $f_7$  was initially developed using it. It is suspected that  $L$  became a function when Chepil (1962) applied  $f_6$  to use short-term tunnel functions to predict long-term field losses. He was faced with the obvious fact that  $\Delta x$  would be changing during the 4-month interval of his experiment because of the wind vector changing its angle. However, even if he had not been considering time span differences, he would have had to resolve the problem that for any real rectangular field oriented at some angle to the wind there are an infinite number of "field lengths" as opposed to one field length for a tunnel.

Chepil resolved this space integration problem (Chepil et al., 1964) by defining  $L$  as

$$L = w \sec A; \quad 0^\circ < A < 85^\circ. \dots \dots \dots [8]$$

where  $A$  is defined as the angle between side  $w$  of the field and the positive  $x$  axis and is called the prevailing wind erosion direction.  $L$  is essentially any chord which is of size  $L$  and parallel to the  $x$  axis. This value of  $L$  allows one to visualize the possibility of three subareas within the total area—those where the chord is constant and of value  $L$  and two equal areas where the chords are not constant and are less than  $L$ . Prediction of  $E$  based on an  $L$  computed from equation [8] will always overpredict, except when  $\beta$  is some multiple of  $\pi/2$ , since some of the area has chords less than  $L$ . However, for the purpose for which the wind erosion equation was developed, i.e., for estimating the effect of conservation practices in reducing wind erosion, the equation is adequate. One other constraint is required to make equation [8] practical, i.e.,

$$L = \begin{cases} w \sec A & L \leq (l^2 + w^2)^{1/2} \\ l \csc A & \text{otherwise} \end{cases} \dots \dots \dots [9]$$

Equation [9] puts limits on  $L$  so that it cannot become larger than the main diagonal of the rectangle. From this then, it can be seen that  $L$  will range from  $w$  to  $l$  as  $\beta$  (or angle  $A$ ) varies through  $\pi/2$  radians, with a maximum as calculated from equation [9].

Chepil visualized the time-averaging effect by his concept of prevailing wind erosion direction, i.e., angle  $A$  (Chepil et al., 1964). This angle is determined by constructing a wind erosion rose, which is a set of 16 normalized vectors whose magnitudes are proportional to the time weighted sum of the average velocity cubed. By selecting the maximum vector which would fit within the rose, one assigns the angle of this maximum vector as the angle  $A$ . Here we see not only time influencing the selection of "the angle" but also a weight factor of the cube of the average velocity. It is interesting to note that Chepil et al. (1964) and Bondy et al. (1980) both used a form of an energy factor to apportion yearly soil loss. Chepil et al. (1964) apportioned within an arc and Bondy et al. (1980) within a time interval.

Skidmore (1965) and Skidmore and Woodruff (1968) made two modifications to Chepil's method of determining  $L$ . First, they determined the prevailing

wind direction by decomposing the 16 normalized vectors into tangential and normal components about an arbitrary coordinate system. The sum of the magnitudes of the normal components divided by the sum of the magnitudes of the tangential components was then maximized by rotating this new coordinate system. The resultant angle between the x axis and east was considered the prevailing wind direction.

Skidmore (1965) did not use this angle to substitute into equation [8] to determine a single L, but instead used his prevailing wind direction angle in conjunction with his field angle and 16 vector angles to determine 16 field lengths by application of equation [8]. To each length he assigned a probability based on the relative energy computed for each L and consequently developed a cumulative probability density function. From this he selected a median value of L which was designated as "the equivalent field width". This latter width was used as the L in equation [2],

It appears that Skidmore's use of a distribution function over space would approximate more closely the idea of integrating over the field than the selection of a worst case L.

### Vegetative Factor Analysis

The effect of vegetation on relative soil loss is represented in the wind erosion equation by  $f_8$  of Fig. 2, i.e.,

$$\tilde{E}_s = \tilde{E}_4 1.75^{-V} \dots \dots \dots [10]$$

where

$$V = V_i(R) \dots \dots \dots [11]$$

and i indexes the combinations of crop, height, and orientation. Typical graphs of equation [11] can be found in Woodruff and Siddoway (1965) for small grain and sorghum. Subsequent publications (Woodruff et al., 1974; Lyles and Allison, 1980, 1981) have not presented vegetative functions but have developed "small grain equivalence" curves. This concept implies that for any given  $\tilde{E}_s$ , there is a single value of R for each  $V_i$  (which are most likely different) which has an equivalent effect on inhibiting soil loss. By adapting a reference i, a single vegetative function can be used in equation [10], if the equivalent values for different i's are used with it. This equivalence concept implies that

$$V_1(R_1) = V_2(R_2) \dots = V_r(R_r) \dots \dots \dots [12]$$

By solving equation [12] for  $R_r$ , we have

$$R_{r_i} = V_r^{-1} \{ V_i(R_i) \}, \quad i = 1, 2, \dots \dots \dots [13]$$

or equivalently

$$S_i \triangleq R_{r_i}$$

which are called small grain equivalence curves, since the reference adopted is flat small grain (Lyles and Allison, 1981). It appears that this concept was first used by Craig and Turelle (1964) so that their graphical form of the wind erosion equation could have  $R_r$  as a parameter rather than  $V_i$ .

In the initial formulation of the wind erosion equation (Woodruff and Siddoway, 1965), multiple simultaneous vegetative cover is not considered. In fact, the crop and its condition is that which exists during "severe blowing time." Craig and Turelle (1964) and Lyles and Allison (1980) considered multiple cover by computing a mixture small grain equivalent ( $S_m$ ), i.e., equation [3] from Lyles and Allison (1980) is:

$$S_m = \prod_{i=1}^n (S_{it})^{P_i} \dots \dots \dots [14]$$

where

$$P_i = R_i / \sum_{i=1}^n R_i \dots \dots \dots [15]$$

$$\sum_{i=1}^n P_i = 1, \dots \dots \dots [16]$$

and  $S_{it}$  is the small grain equivalent for crop i, based on the total mixture weight. Equation [14] is a weighted product which satisfies the following two criteria,

$$(S_{it})_{\min} \leq S_m \leq (S_{it})_{\max} \dots \dots \dots [17]$$

and

$$S_m \rightarrow S_{k_i} \quad i = 1, 2, \dots, k, \dots, n \dots \dots \dots [18a]$$

as

$$P_k \rightarrow 1 \dots \dots \dots [18b]$$

Craig and Turelle (example F-3, page 30, 1964) used a simple sum, i.e.,

$$S_m = S_1 + S_2 \dots \dots \dots [19]$$

Here each  $S_i$  was computed based on its own weight rather than the total for the mixture. The use of  $S_{it}$  in equation [14] guarantees the effect shown in equation [17], which would not be true if the component weights had been used. The inherent assumption in equation [19] is that the concept of equivalency, i.e., equation [12], is also true when the components are mixed. This assumption appears to be questionable.

A more general approach to computing the effect of mixtures should be based on equation [10], which is related to soil loss, rather than equivalency of either  $V_i$  or  $S$ . Other methods of combining component equations such as a linear combination, e.g.,

$$E_{5m} = \sum_{i=1}^n P_i E_{5it} \dots \dots \dots [20]$$

cannot be justified any more than the product form implied in equation [14] until more data are available.

### Modifications

EPIC provides the framework to sum the effects of the various factors that affect soil loss and hence productivity. From the point of view of soil loss by wind, this is equivalent to summing the daily soil loss surface density. This is expressed analytically by rearranging equation [4] into

$$E_{EPIC} = \frac{1}{T} \sum_{i=1}^n \left\{ \frac{1}{A} \int_y \int \Delta t_i q \, dt \, dy \right\} \dots \dots \dots [21]$$

where the bracketed quantity represents the daily soil loss per unit area,  $m_i''$  and  $T$  the simulation period.

From the arguments presented in the previous sections, it can be visualized that the modifications to the wind erosion equation must produce the equivalent of the daily soil loss surface density shown in brackets in equation [21]. EPIC does the summation for  $n$  days, where  $n$  is chosen prior to simulation.

Equation [21] has the order of integration of  $t$  and  $y$  reversed, as compared to that in equation [4]. This implies that the  $q$  as computed does not change during the day, i.e., it is a daily average. This assumption then restricts the  $y$  integration for a fixed wind angle,  $\theta$ , which results in a simple computation of  $L$ , in that there is only one integration over the field in the  $y$  direction for 1 day.

In essence, the problem of inputs changing over the period of computation has been simplified but not changed. Variables such as  $I$ ,  $K$ , and  $V$  can now be considered essentially constant for a single day, but  $L$  will change as it is easily visualized that  $\theta$  and  $u$  are changing on a shorter time scale than EPIC's computation iteration rate of 1 day. Hence we are faced with converting  $q$  to some daily average value. This is similar to Chepil's problem of how to convert from short-time, essentially continuous, relative soil loss with fixed input variables to absolute soil loss for a year. Here we have to go from short-term to 1 day rather than 1 yr, but the problem remains since the description of the wind variable that drives the soil loss still fluctuates considerably during the 1-day period.

The justification is based on the argument used in calculus when passing to a limit, i.e., that a sum based on finite increments becomes exactly equal to the integral as the differential approaches zero. This is identical to the justification of approximating solutions to differential equations by finite differences. Here then we claim that long-term calculations of soil loss based on daily averages will approach that based on the original experimental short-term data more closely than a single calculation for 1 yr.

The above argument presupposes that  $q$  is available! This is hardly the case, although from the discussions related to Fig. 2 it might be concluded that  $q$  is obtainable from the wind erosion equation by "peeling" off  $f_6$ . Due to the present uncertainty as to how some of the core functions,  $f_5$ ,  $f_7$ ,  $f_8$ , and  $K$ , were developed, this is not deemed practical. Also, the problem of transforming from a "relative soil loss" to an absolute would have to be resolved. The latter, under the time constraints of building EPIC, was virtually impossible.

Another approach, based on the method used by Niles (1961), appears to be a reasonable approximation to obtaining a daily integration of  $q$  with time from the wind erosion equation. Niles (1961) computed the relative soil loss and as a final step converted to absolute amounts via Table 3 of Chepil (1960). While we know  $f_6$  and could apply it in its inverse form to get a relative erodibility, we would not be any better off since we are back to a relative quantity. What is needed, then, is a relationship which, when applied to  $E$ , would approximate the integration function of  $f_6$  and not its relative to absolute transformation capability.

The best available function that would approximate this desired function is that involving a single multiplication factor called the erosive wind energy

factor (Bondy et al., 1980). We have extended this concept by shortening the periods of interest from months to a single day. Bondy et al. (1980) used a monthly factor to subdivide  $E$  while allowing the  $I$ ,  $K$ ,  $L$ , and  $V$  factors to take on values for the periods under consideration.

The assumption that the soil loss is directly proportional to the erosive wind energy is implied by equation [22] which computes period average soil loss flux, i.e.,

$$E_i = r_i E \dots \dots \dots [22]$$

where  $r_i$  is the erosive wind energy factor for the  $i$ -th period. If  $E$  has units of  $t/(\text{ha}\cdot\text{yr})$ , then  $E_i$  has units of  $t/(\text{ha}\cdot\text{day})$ .

To utilize equation [22] with equation [21] requires that  $m_i''$  be determined, i.e.,

$$m_i'' = \Delta t_i E_i.$$

However, since  $\Delta t_i$  in EPIC is 1 day, both variables are numerically equal and, consequently,  $E_i$  can be summed as if it were  $m_i''$ .

The erosive wind energy factor is calculated as

$$r_i = e_i / \sum_{i=1}^n e_i \dots \dots \dots [23]$$

where

$$e_i \triangleq \int_{\Delta t_i} \dot{W} dt \dots \dots \dots [24]$$

or equivalently

$$e_i = c_i \langle u_e^3 \rangle_i \Delta t_i \dots \dots \dots [25]$$

Equation [25] is derived from equation [24] by expressing the work rate,  $\dot{W}$  in terms of the steady state form of the first law of thermodynamics, i.e.,

$$\dot{W} = \begin{cases} P - \dot{Q} & u > u_t \\ 0 & u \leq u_t \end{cases} \dots \dots \dots [26]$$

where

$$P = \int_{A_3} \tau_{zx}(z) u(z) dx dy \dots \dots \dots [27]$$

and  $\dot{Q}$  is zero for all  $u > u_t$ . Equation [27] expresses the total power flow into a rectangular control volume that represents the boundaries of a one-dimensional fluid flow soil loss system.

For application to EPIC, equations [22], [23], and [25] are used, with the index  $i$  representing the  $i$ -th day and the upper limit  $n$  in equation [23] the number of days in a year. The value of  $\langle u_e^3 \rangle$  on a daily basis is computed using a regression equation relating it to  $\langle u \rangle$ . This regression equation was developed from the following two equations, assuming that the daily windspeed is distributed as a two parameter Weibull distribution  $p$ , i.e.,

$$\langle u_e^3 \rangle = \int_{u_t}^{\infty} u^3 p(u, k, c) du \dots \dots \dots [28]$$

where

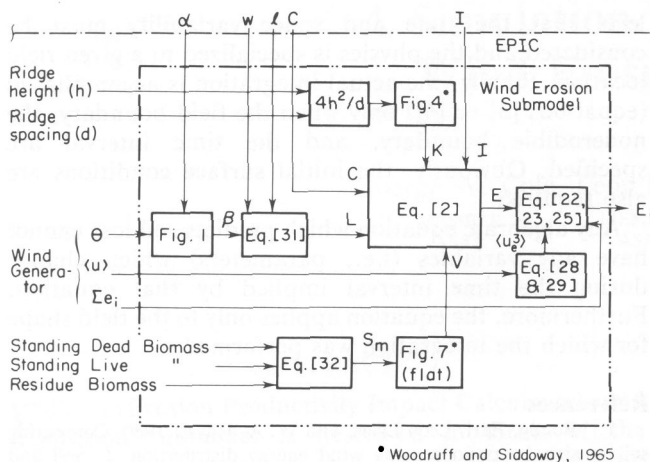


Fig. 3—A block diagram of the wind erosion submodel and its interfaces within EPIC.

$$k \triangleq 2$$

$$c \triangleq 1.12 \langle u \rangle \dots \dots \dots [29]$$

Equation [28] is derived from the standard definition of the third moment of the distribution  $p$ . For erosive wind, the integration is for all values greater than the threshold value,  $u_t$ . Fig. 3 illustrates how these modifications fit into the wind erosion submodel.

Having now dealt with the time integration of  $q$  in equation [21], the integration with respect to  $y$  must be considered. If, as in the previous argument, we claim that the application of the erosive wind energy factor approximates to removing the time integration from  $E$ , we might also attribute it with the capability of removing the crosswind or  $y$  component of integration. Recall that prior to the application of  $f_0$ , the "width" of the relative erodibility was that of a tunnel or narrow field strip and, therefore,  $L$  was independent of  $y$ .

An alternate hypothesis would be that because Chepil et al. (1964) utilized a single worst case  $L$ , i.e., equation [8], the value of  $E$  would imply a rectangular field of width  $w$  and length  $L$  that is aligned on the  $L$  side with the average wind vector. Here again  $L$  is independent of  $y$ . In other words, to get the effect of varying  $L$  into  $E$ , the effect was accomplished external to the wind erosion equation!

To properly incorporate the effect of a varying  $L$  with  $y$  would require integration of equation [22] over  $y$  for each day or equivalently for each field angle  $\beta$ . This would be equivalent to perhaps 10 to 20 computer solutions of equation [22] per time step, depending on the size of  $\Delta y$ .

By adopting a scheme where "an  $L$ " is selected that

yields the "correct answer", one can reduce the number of computations. This is in essence what Chepil implies by his worst case estimate and also what Skidmore (1965) implies by his time weighting concept.

Since neither approach appears to be founded upon actual integration of  $q$  with  $y$ , it appears that any reasonable scheme that satisfies

$$0 < L < (\ell^2 + w^2)^{1/2} \dots \dots \dots [30]$$

would be an adequate approximation. We selected an average of the chords as they vary in  $y$ , which for a rectangular field of  $\ell$  and  $w$  oriented at  $\beta$  is

$$L = \frac{\ell w}{w|\cos \beta| + \ell|\sin \beta|} \dots \dots \dots [31]$$

While equation [31] is arbitrary, it does satisfy the criteria of equations [30] and [7] and is simple to compute.

Finally, we come to the method used in EPIC to simultaneously handle the effects of a growing crop and a residue from a previous crop.

Due to the paucity of mixture data, a modification of the method of Lyles and Allison (1980) was proposed. That is

$$S_m = \sum_{i=1}^n P_i S_{it} \dots \dots \dots [32]$$

However, based on a further simplification in the functional form of  $S_i$ , the actual implementation into EPIC takes the form of equation [19]. That is, assuming that the  $S_i$  are linear over the range of interest, then equation [32] degenerates to a sum of  $S_i$ .

### SIMULATION RESULTS

No measured data sets of erosion amounts are available for validating EPIC modifications of the wind erosion equation (WEE). Using representative soils, crop rotations, and management operations for various states in the Midwest, Great Plains, and West, we compared erosion amounts between EPIC and the WEE using current procedures (Bondy et al., 1980). We chose four locations to give geographic coverage and five crop rotations common to those locations (Table 2).

Except for rotation 4, the WEE amounts were larger than those estimated by EPIC. However, agreement between EPIC and WEE for rotations 2 and 3 was excellent, fair for rotations 1 and 5, but poor for rotation 4.

Possible reasons for differences between the two methods of estimating wind erosion include:

TABLE 2. WIND EROSION ESTIMATES FROM EPIC AND WEE FROM SELECTED CROP ROTATIONS AND LOCATIONS IN THE U.S.

| Crop rotation—<br>number, sequence      | Location—<br>county, state | Soil                        | Av. estimated soil loss |      |
|---|----------------------------|-----------------------------|-------------------------|------|
|   |                            |                             | EPIC*                   | WEE  |
|   |                            |                             | t/(ha • yr)             |      |
| 1. Corn-soybeans                        | Monona, IA                 | Luton silty clay            | 7.3 ± 3.0               | 12.1 |
| 2. Wheat-corn-fallow                    | Redwillow, NE              | Keith silt loam             | 0.13 ± 0.21             | 0.23 |
| 3. Irrigated corn                       | Sherman, KS                | Keith silt loam             | 6.0 ± 4.3               | 6.2  |
| 4. Wheat-alfalfa-<br>alfalfa            | Curry, NM                  | Amarillo loamy<br>fine sand | 71.3 ± 29.3             | 25.2 |
| 5. Wheat-wheat-fallow-<br>grain sorghum | Curry, NM                  | Amarillo loamy<br>fine sand | 29.3 ± 24.6             | 37.2 |

\* 50-year average.

1. EPIC uses mixing coefficients for various management (tillage) operations for distributing crop residue among buried, flat, and standing dead biomass categories. Some residues are always left in the standing dead category regardless of tillage operation. In using the WEE, we assumed that certain tillage operations (e.g., moldboard plowing and disking) flattened all the residues. Flattened residues are not as effective as standing residues in controlling wind erosion.

2. EPIC has residue decomposition equations that are applied daily. In the WEE, an average overwinter residue loss, usually 15 to 30%, is applied at the end of the winter period in the rotation.

3. Simplified forms of the small-grain equivalent equation are used in EPIC, while the original equations are used in solving the WEE.

4. Simulated wind data are used in EPIC. Actual long-term average data are used in the WEE.

5. A daily L factor is applied in EPIC, whereas a weighted approach by periods is used to determine L for application in the WEE.

The large difference in rotation 4 is apparently due to EPIC's incorrect handling of dry matter production during establishment and early growth of perennial crops—in this case, alfalfa (Jimmy Williams, personal communication).

Our interest in this paper is not to assess the validity of EPIC. However EPIC's above-ground (biomass) production (excluding grain) has a major impact on wind erosion estimates. Except for alfalfa, we used average biomass outputs of EPIC in solving the WEE. Consequently, values in Table 2 are not realistic unless EPIC accurately predicts dry matter production.

### CONCLUSIONS

The 50-yr simulation results of EPIC compare favorably with the wind erosion equation calculation of soil loss for the period of the crop rotation sequences. These results suggest that the use of the erosive wind energy factor (Bondy et al., 1980) can be extended to a daily time interval when the daily soil losses are recombined for a long-term prediction. It further appears that the simulated daily wind velocity is adequate for computing the erosive wind energy factor and that the methods used for computing L and V are also adequate.

Based on the wind erosion equation analyses, it is clear that any future soil loss prediction equations must include three things. First, the physics of the erosion process must be represented as either a point flux  $f$  or a line intensity  $q$  (equation [5]), the former being the ideal. Second, any variables that affect  $f$  or  $q$  must be described independently in time and space (e.g.,  $f_4$  in equation [3]). This implies that the functional relationships are either given for a specific case or that they are agreed upon as representative for predictive purposes. It is at this flux

level that the time and space variability must be considered and the physics is specialized to a given field location. Finally, the actual integration is accomplished (equations [3] or [4]) only when the field boundary, the nonerodible boundary, and the time interval are specified. Obviously, the initial surface conditions are also required.

Any algebraic equation which predicts soil loss cannot have any variables (i.e., parameters) which change during the time interval implied by that equation. Furthermore, the equation applies only to the field shape for which the integration was performed.

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