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Some Wind Erosion Process Measures

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ABSTRACT

RELATING the various damaging effects of soil erosion by wind to the appropriate measures of the erosion process are critical for controlling and estimating the probable damage. A method is outlined using the conservation of mass and momentum principles showing how the cause and effect measures can be related. The method is demonstrated by applying it to three possible damaging effects, i.e., crop yield, soil loss from the field, and plant damage by abrasion.

INTRODUCTION

Recent developments in the methods for predicting soil loss from a field due to wind erosion (Cole, 1984a; 1984b) have pointed to the importance of knowing not only the dimension of the variable that quantifies the effect of erosion but also a verbal description of its meaning. For example, the definitive reference for what is commonly known as the wind erosion equation (Woodruff and Siddoway, 1965) refers to the equation that predicts the average soil loss rate per unit area. The symbol assigned to the variable was E_c,* with units of tons/(acre·annum). Very little insight was provided in Woodruff and Siddoway (1965) as to the *meaning* of E_c. As pointed out in Cole (1984b), it represents the statistical mean of the time and the spatial average of the *normal component* of the surface soil flux vector. Recognition that the vector could be integrated in time and over the field surface leads to the understanding of the meaning of E_c. The significance of this method is that it allows "prediction" of E_c for any flat field whose perimeter delimits a convex region, given the soil flux vector and the required input functions. Furthermore, this method has necessitated defining the soil loss accounting interval (Cole, 1984b) to be any time interval within a crop rotation period, perhaps of 2- or 3-years duration.

For "total" soil loss, where total refers to all size fractions contained in the eroding mixture, E_c appears to be a reasonable measured of soil loss by wind erosion. As shown in Cole (1984b), it is not the only measure of soil loss, i.e., by changing the interval of soil accounting from 1 year (as implied by E_c), one could consider the average January soil loss, which also has the same dimensions as E_c but a different meaning. Obviously then, the units are necessary but not sufficient to define the measure. To avoid confusion with E_c, the symbol W has been adopted to allow differentiation of the time intervals.

For other undesirable effects of the wind erosion process, e.g., onsite crop damage, other measures must be defined in order to (a) determine when the effects can no longer be tolerated, and (b) develop some method of predicting these measures.

It is the objective of this paper to illustrate how one can, from first principles and other constraints, develop measures of the soil erosion process and, secondarily, to note the interrelationship between the various measures.

DISCUSSION

In order to aid in the following analysis, we shall differentiate between the effect of the process and the process itself. The process of wind erosion, as defined here, is primarily concerned with the motion of the soil particles. (All other processes, such as saltation, abrasion, etc. are considered as subprocesses.) The effects are the result of the process, such as changes in soil depth, plant yield, plant damage, etc.

Determining if the erosion process is acceptable to some degree requires that limits be placed on the appropriate erosion process variable. These limits are determined by first selecting the tolerable range of the effected variable and then determining the range of the erosion process variable that would cause it. For example, by selecting the maximum depth that can be eroded, we can determine (in conjunction with other constraints) an acceptable upper limit on the soil erosion rate.

Here we have chosen not to consider the range of acceptable numerical values, i.e., the tolerance limits, because that problem, although very important (Schmidt et al., 1982; Stamey and Smith, 1964), should not confound the problem of the relationship between cause and effect. We limit our analysis to determining those measures of the erosion process that would relate to a specified effect, e.g., we will select the change in yield as an effect and relate it to the soil flux, f, at a point on the field. This flux then is the appropriate measure of the wind erosion process for this case. We will also show, in contrast to a point measure, that W, a measure related to the total soil loss for the field, relates only to the spatially averaged depth change of the field. Both measures, W and f, have the same dimensions and are related, but they are different, and the degree of tolerance of f and W must, in general, be related to the individual effects, i.e., yield and depth, respectively.

In the following sections, we develop the two measures just cited plus a third, which is related to plant damage due to particle motion.

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*The symbol E_c has been substituted here for the original symbol E, to avoid confusion with the expectation operation used later, i.e., $E(\cdot)$.

YIELD-EROSION ANALYSES

This analyses is dependent on the existence of a set of functional relationships, which together link the erosion process and the concept of soil productivity. Williams et al. (1982) has such a set in their Erosion Productivity Impact Calculator (EPIC) model. Here we shall not deal explicitly with all of EPIC's equations but symbolically, by grouping a subset of these into two equations, which we call the crop flux function and the erosion process function.

We shall assume, like The National Soil Erosion-Soil Productivity Research Committee (1981) and Krauss and Allmaras (1982), that the concept of soil productivity is adequately meaured by the rate at which the soil allows biomass to be produced, i.e., crop yield. In order to emphasize the fact that yield, p, is a measure that depends upon the accumulation of biomass from a specified region, A, for given interval of time, T, we postulate the existence of the following relationship:

$$p = \frac{1}{AT} \int_T \int_{S_1} c \, dA \, dt \quad \ldots\ldots\ldots\ldots\ldots\ldots [1]$$

where c is defined as the crop flux. (All symbols are defined in Table 1.) Equation [1] is a restatement of the more familiar definition of crop yield,

$$p = m_c/(AT) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [2]$$

where m_c is the mass of the crop accumulated from A during T. Comparison of equations [1] and [2] shows that m_c is defined as the time and space integrals of the crop flux.

The concept of a crop flux is analogous to the mass flux of fluid mechanics (Bird et al., 1960) and, consequently, many of the concepts and much of the terminology are also applicable here. Cole (1984a, 1984b) has previously applied these flow concepts to soil erosion prediction.

Now equation [1] is sufficient for describing "productivity", if all the independent variables of c can be specified as functions; however, this is not the case. Some of these variables will be random, in a statistical sense, and hence p is random even though the function c is deterministic. Consequently, to use equation [1] in a predictive sense implies that the best we can do is to predict the statistical average and/or the variance of the distribution of p. Therefore, we take as our definition of the average productivity the expected value of p,

$$Y = E(p) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [3]$$

where $E(\cdot)$ is the averaging operation of statistics. We explicitly make this point since p is also an average but in the sense of calculus; thus, Y is the statistical average of a time and space average.

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

Symbol	Definition and dimensions
A	the projected area of the field surface on the x,y plane, L^2
B_i	any of the independent variables of the crop flux function, other than h, dimensions unknown
c	crop flux, $M\,L^{-2}T^{-1}$
e	erosion function as defined in Stamey and Smith (1964), $M\,L^{-2}T^{-1}$
$E(\cdot)$	statistical mean, dimensions vary
E_c	potential average annual soil loss as defined in Woodruff and Siddoway (1965), $M\,L^{-2}T^{-1}$
F	force vector, $M\,L\,T^{-2}$
f	soil flux vector, $M\,L^{-2}T^{-1}$
g	soil genesis flux, $M\,L^{-2}T^{-1}$
G	expected value of the time and space average of g, $M\,L^{-2}T^{-1}$
h	distance from the soil surface to top of the c horizon and, equivalently, the thickness of the control volume or solum, see Fig. 1, L
m_c	the crop mass, M
p	the time and space average of c or, equivalently, the yield, $M\,L^{-2}T^{-1}$
r	renewal function as defined in Stamey and Smith (1964), $M\,L^{-2}T^{-1}$
R	the volume of the control volume, L^3
S	surface area of R, the control volume, L^2
S_i	surface area of the i-th surface of the control volume, L^2
S_p	surface area of a plant, L^2
s	stress tensor, $M\,L^{-1}T^{-2}$
T	a time interval, T
t	time, T
V	velocity of the particle flow relative to the surface S_1 or S_2, $L\,T^{-1}$
$\hat{V}$	velocity of the particle flow relative to the x,y,z coordinate system, shown in Fig. 1, LT^{-1}
V_S	velocity of the control volume surface relative to the x,y,z coordinate system, shown in Fig. 1, LT^{-1}
W	the expected value of w, or average soil erosion, $M\,L^{-2}T^{-1}$
w	the time and space average of the normal component of the surface soil flux vector, or soil erosion, $M\,L^{-2}T^{-1}$
x	distance along the x axis, L
y	distance along the y axis, L
Y	the expected value of p, $M\,L^{-2}T^{-1}$
z	distance along the z axis, L
ρ	soil bulk density or soil concentration, $M\,L^{-3}$
Subscripts	
i	index, 1, 2, 3 . . . various surfaces and/or independent variables of c
n	normal component, or upper limit of an index
x	x component
y	y component
z	z component
Superscripts and other symbols	
$\rightarrow$	vector
$<>_{\Delta x}$	an average of the function within the brackets with respect to an interval that is shown here as Δx. If the interval is unambiguous, it is omitted.
$\triangleq$	defined

Crop Flux Function

At present we do not know the form of the crop flux function, and we only imperfectly know its independent variables. McCormack et al. (1982) identify some of these variables as "the soil rooting depth, topsoil thickness, available water capacity, plant nutrient storage, surface runoff, soil tilth, and soil organic matter content." The National Soil Erosion-Soil Productivity Research Planning Committee (1981) cites the four most important variables, which are influenced by soil erosion, as loss of plant-available soil water capacity, plant-nutrient losses, degradation of soil structure, and nonuniform removal of soil within a field. They stress further the relationship of soil water capacity to changes in the capacity of the root zone or reduction of the depth of the root zone. Krauss and Allmaras (1982), citing the work of Wetter, indicate that "winter wheat yields were a linear function of measured epipedon thickness ranging from 0 to 61 cm." Pierce et al. (1983) relate their measure of productivity, i.e., a productivity index, to a "sufficiency" of available water capacity, bulk density, and pH when all other factors, such as climate and nutrients, are not limiting plant growth.

We see then that many factors affect yield; however, the concept of soil depth of the rooting zone pervades these. For simplicity in our analyses, we shall assume that the major effect of soil erosion is related through the depth of the rooting zone, h, or equivalently the thickness of the solum. This is represented as

$$c = c[h(x,y,t), B_i(x,y,t)] \quad \ldots\ldots\ldots\ldots\ldots\ldots [4]$$

where B_i represents all other i independent variables. Some of the B_i would also be related to the wind erosion process, e.g., the effect on surface soil density due to sorting. For generality, we show these variables as functions of x, y, and t. The functional form of equation [4] is unknown and, as implied by a model such as EPIC, the function is really a set of many equations. The combination of equations [1] and [4], however, provides a method of conceptually relating yield to the depth of soil. However, what is still lacking is a relationship of depth to the soil erosion process.

Erosion Process Function

Stamey and Smith (1964), while providing the basis for a definintion of an "erosion tolerance", put forth a general equation that is based on the relationship between the time rate of change of a soil property and the soil property. Stamey and Smith did not restrict this concept to any particular property; however, many of their examples (Smith and Stamey, 1964; Smith and Yates, 1968) utilized rooting depth as a property.

Considering depth of soil as a property, then the Stamey-Smith inequality (Stamey and Smith, 1964, equation [3]) can be modified to

$$h(x,y,t) = \frac{1}{<\rho>_h} \int_0^t g[x,y,z_1(x,y,t),t]$$

$$- f[x,y,z_2(x,y,t),t] \; dt \; + h(x,y,0) \quad \ldots\ldots\ldots\ldots [5]$$

Equation [5] expresses the fact that the depth, h(x,y,t), below any point on the field surface can be computed from a knowledge of the average density of the soil within h, the initial depth, and the soil flux vectors at the top and bottom surfaces. In order to show that equation [5] can be rigorously defended, we diverge temporily from our main derivation to show how equation [5] can be developed from first principles. Those not interested in the details may continue at the Yield-Erosion Function section of the paper.

Depth Function Derivation

We show here the derivation of equation [5] and its equivalence to the Stamey-Smith equation (Stamey and Smith, 1964, equation [3]) when the "property" to be conserved is the depth of the soil.

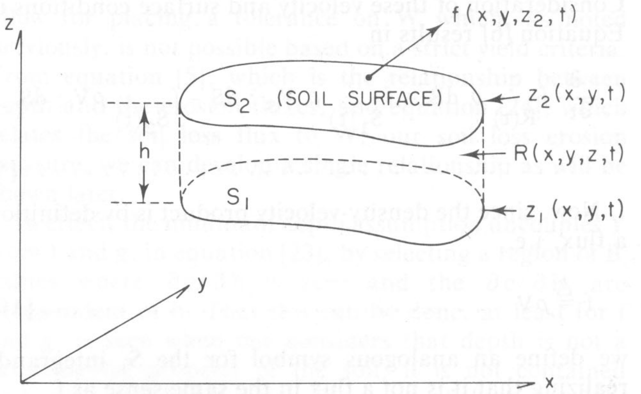

Fig. 1—The control volume of the soil, below surface S_2, showing its relationship to an x,y,z coordinate system and the soil loss flux vector, f. The volume R contains only the solum.

The region of interest of soil, known as the solum, is depicted in Fig. 1 as R(x,y,z,t). The "soil surface," S_2 at $z = z_2$, is affected by both erosion and deposition, where z_1 changes due to soil genesis only and is represented by the movement downward of S_1, which is the top surface of the C soil horizon. z_2 may move in either direction, depending on which process predominates. For simplicity, we exclude such processes as tillage which, in the short-term, would affect z_2, since we might reasonably expect the soil to be compacted by other processes which would compensate for the tillage in the long-term.

Starting with the conservation-of-mass principle as applied to the control volume of Fig. 1, we have (from page 78, Shepherd, 1965)

$$\int_S \rho V \cdot ds = -\frac{\partial}{\partial t} \int_R \rho \, dR \quad \ldots\ldots\ldots\ldots\ldots\ldots [6]$$

(The use of the mass-conservation principle for soil particles is an assumption that has been discussed by Cole, 1984a.) Now equation [6] is predicted on a control volume that is stationary; however, since ours is moving due to the processes involved, we must modify equation [6] by allowing S, the surface, and R, the volume, to change in time. *p* represents the soil density and V the velocity, a vector, of the particles at the surface of R, relative to that surface.

Assuming no motion of the soil, except possibly at the S_1 and/or S_2 surfaces, allows the surface integral to be taken only over S_1 and S_2. The definition of V can be expanded to show its relative nature and thereby develop mass flow rate terms for the top and bottom surfaces of S, i.e.,

$$V(x,y,z,t) = \hat{V}(x,y,z,t) - V_S(x,y,z,t) \quad \ldots\ldots\ldots [7]$$

where $\hat{V}$ is the particle velocity relative to the coordinate system, which is fixed at a stationary point within the earth and well below S_1 (see Fig. 1). V_S is the velocity of the surface that the particles would be "passing through", again relative to the coordinate system.

At S_2 we have both particle motion and surface motion, hence V is applicable; however, at S_1 the particle velocity is zero and, therefore, soil genesis is assumed to be represented by a motion of the surface hence

$$\hat{V}(x,y,z_1,t) = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots [8]$$

Consideration of these velocity and surface conditions in Equation [6] results in

$$\frac{\partial}{\partial t}\int_{R(t)} \rho \, dR = \int_{S_1(t)} \rho \, V_S \cdot dS - \int_{S_2(t)} \rho V \cdot dS \qquad [9]$$

Now, since the density-velocity product is by definition a flux, i.e.,

$$f \overset{\Delta}{=} \rho V \qquad [10]$$

we define an analogous symbol for the S_1 integrand, realizing that it is not a flux in the same sense as f,

$$g \overset{\Delta}{=} \rho V_S \qquad [11]$$

However, we shall refer to g as a soil genesis flux, since the surface "motion" is attributed to soil genesis.

To obtain h, the solum thickness or equivalently the depth of the top of the C layer, from equation [9] requires the integration of the density integral and results in

$$\int_R \rho dR = < \rho >_R \; < h >_A \; A \qquad [12]$$

where A is the projected area of S_1 or S_2 on the x,y plane and

$$h \overset{\Delta}{=} z_2 - z_1 \qquad [13]$$

(For simplicity we shall refer to h as the depth, realizing that it is not any depth.) Substitution of equations [10], [11], and [12] into equation [9] and dividing by A results in

$$\frac{\partial}{\partial t}(< \rho >_R \; < h >_A) = \frac{1}{A} \left\{ \int_{S_1} g \cdot dS - \int_{S_2} f \cdot dS \right\} \qquad [14]$$

Now we allow A to approach zero so that the spatial averages of equation [14] approach their integrands and equation [14] becomes

$$\frac{\partial}{\partial t}(< \rho >_h h) = g - f \qquad [15]$$

We note that, in passing to the limit, the volume average density becomes an average in h and that the projected area average of h becomes h.

If we assume that $<p>_h$ is either not a function of time or at most a weak function, then it can "pass through" the derivative in equation [15], yielding

$$< \rho >_h \frac{\partial h}{\partial t} = g - f \qquad [16]$$

Rearrangement and integration of equation [16] in time yields equation [5].

The similarity of equation [5] to the Stamey-Smith (1964) equation [3] can be seen as follows. The Stamey-Smith equation has as its integrand the difference between the "erosion rate" of the property e(x,y,t), and its "renewal rate," r(x,y,t). Neither of these functions consider where these rates exist on R. The equivalency between e and r and f and g is established by the following relationships, i.e.,

$$f(x,y,z_2,t) = e(x,y,z_2,t) - r_2 \, (x,y,z_2,t) \qquad [17]$$

$$g(x,y,z_1,t) = r_1(x,y,z_1,t) \qquad [18]$$

$$r \overset{\Delta}{=} r_1 + r_2 \qquad [19]$$

then

$$g - f = r - e \qquad [20]$$

where equation [20] represents Stamey and Smith's (1964) "net change tolerance" function.

Substituting equation [20] into equation [5] and considering the density shows the equivalency of equation [5] with equation [3] of Stamey and Smith (1964). Actually, these authors did not explicitly consider the erosion of the depth "property" in their derivation and hence did not have to consider how and in what form the soil density would enter their equation. It is obvious that the conservation-of-mass principle results in an equation for the depth that requires less "patching" and indicates where the mass fluxes are physically located and how the soil genesis rate (r_1) is different than the surface renewal rate (r_2).

Yield-Erosion Function

In order to determine the yield as a function of the measures of the erosion process and soil genesis process contained in equation [5], we could substitute equation [5] into equation [4] and then the result into equation [1] and, finally, that result into equation [3]. However, more insight is gained by the following representation, which involves the following steps.

First, we obtain the time derivative of c, i.e.,

$$\frac{\partial c}{\partial t} = \frac{\partial c}{\partial h}\bigg|_{B_i} \frac{\partial h}{\partial t} + \sum_{i=1}^{n} \frac{\partial c}{\partial B_i}\bigg|_{h} \frac{\partial B_i}{\partial t} \qquad [21]$$

Then, upon integration of equation [21] we get

$$c(x,y,t) = \int_0^t \frac{\partial c}{\partial h} \frac{\partial h}{\partial t} \, dt + \sum_{i=1}^{n} \int_0^t \frac{\partial c}{\partial B_i} \frac{\partial B_i}{\partial t} \, dt + c(x,y,0) \qquad [22]$$

The significance of this form of c is that is stresses the dependence of c on its derivatives, i.e., its sensitivity factors and the time rates of the independent variables of c. For example, the first integral indicates that the contribution to c due to the wind erosion process as it affects the depth of the solum is due to $\partial c/\partial h$, its sensitivity to changes in h, times the rate at which h changes.

To utilize equation [22] to obtain the equation for average productivity in terms of the erosion process requires the sequential substitution of equation [16] into [22] into [1] into [3], which yields

$$Y = E \left\{ \frac{1}{AT} \int_T \int_{S_2} \left[\int_0^t \frac{\partial c}{\partial h} \left(\frac{1}{< \rho >_h} [g - f] \right) dt + \sum_{i=1}^{n} \int_0^t \frac{\partial c}{\partial B_i} \frac{\partial B_i}{\partial t} dt + c(x,y,0) \right] \cdot ds \, dt \right\} \qquad [23]$$

Now equation [23] illustrates the dependence of the average productivity, Y, upon f, as well as the sensitivity factors, the soil genesis flux, and the other B_i. To illustrate the significance of equation [23] requires a knowledge of the standard measure of soil loss by wind erosion which, from Cole (1984b) is

$$W = E \left\{ \frac{1}{AT} \int_{S_2} \int_T f \cdot ds \, dt \right\} \ldots\ldots\ldots\ldots [24]$$

where W is the expected value of the average soil loss flux, f. In the following analysis, we temporarily extend the meaning of W and f to include the loss of soil by water erosion for greater generality.

Comparison of equations [24] and [23] shows that the average productivity is not dependent on the standard measure of soil erosion, W, but on the product of the sensitivity coefficient and the soil loss flux vector. That this is reasonable also can be deduced from the differences in what is implied by f and W. W involves integration over a region, and while it depends on the process flux, f, at every point there are many different f functions that can result in a single value for W yet result in multiple values for Y. For example, one might have a W of zero (no loss from the field) for many different f's, yet different values of Y. From this we can conclude that Y cannot be a function of the standard measure of soil erosion, W.

Since $\partial c/\partial h$ would be expected to depend on the B_i factors (see equation [21]), and the remaining sensitivity factors also may depend on h, the effect of soil erosion on average productivity is, in reality, conditional on the magnitude of all of the B_i factors. The question "What is the effect of erosion on productivity?" is strongly dependent on the values of B_i and, consequently, the question can only be answered after the B_i's are specified!

We note one other important point, i.e., if one puts a limit on Y, then there is no single limit value that one can place on any of the independent variables, e.g., f. For a single Y limit (a tolerance!), there would probably be a multidimensional space of all variables that would satisfy this Y limit, hence one would expect any tolerance that would apply to f must be *a function* of all of the other factors! Consequently, it appears futile to seek a single limit on f, and certainly based on the previous contrast of equations [23] and [24], it would make no sense at all to seek a tolerance on W based on a limit on Y.

Average Depth-Erosion Analyses

The second example of a proper erosion measure selection is illustrated by adding another constraint (or assumption) to the previous example. The required assumption is implied in the generally accepted definition of soil loss tolerance, i.e., ". . . the maximum level of soil erosion that will permit a high level of crop productivity to be sustained economically and indefinitely" (Wischmeier and Smith, 1978, as cited in the preface of Schmidt et al., 1982). The tacit assumption is that some minimum depth of soil is required to sustain some unspecified level of productivity.

This assumption is quite reasonable, and although the determination of the minimum depth may present some difficulty, it is infinitely less difficult than determining the information required by equation [23]. It also does allow for placing a tolerance on W which, as noted previously, is not possible based on a strict yield criteria. From equation [5], which is the relationship between depth and the erosion fluxes, and equation [24], which relates the soil loss flux to W, our soil loss erosion measure, we can develop a single relationship as will be shown later.

In effect, the minimum depth assumption uncouples Y from f and g, in equation [23], by selecting a region of B_i values where $\partial c/\partial h$ is zero and the $\partial c/\partial B_i$ are independent of h. That this can be done, at least for f and g, is seen when one considers that depth is not a fundamental property of the soil, it is not contained within the soil; but it is one dimension of the "container which holds" the soil that has the B_i properties.

The depth so selected could be well above some absolute minimum value and hence more conservative than is absolutely necessary; however, by selecting a "worst case" minimum depth, the problem of determining if erosion has affected yield has been considerably simplified, i.e., equations [24] and [16] vs. equation [23]. The question is now answered in a yes-no context, i.e., yes for all h less than the minimum and no for all h greater than the minimum.

The relationship between h and W can be derived by averaging equation [14] with respect to T and then taking the expected value. The result is

$$\langle \rho \rangle_R \, E \left\{ \frac{\langle h(T) \rangle_A - \langle h(0) \rangle_A}{T} \right\} = G - W$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [25]$$

where G is defined for g in the manner of equation [24] and $\langle p \rangle_R$ is the volume averaged density, which is assumed to be time invariant. If the density cannot be assumed constant, then the volume averaged density at times T and O will appear within the expectation operator braces, as products with their appropriate depths.

Equation [25] indicates that W is the proper measure of soil erosion to relate to the expected value of the average time rate of change of the spatially averaged soil depth, the effect. Of course, a knowledge of $\langle p \rangle_R$ and G also are required for obtaining a numerical value of h. G in the sense used here is considered part of a process, although it is not the wind erosion process but the soil genesis process. It is interesting to note that when one wishes to use an average of a process measure (e.g., W), then one also is constrained to relate this to an average of the effect, i.e., the parenthetical term in equation [25]. This term can be simplified by noting that h(O) and T are not random.

PLANT ABRASION - EROSION ANALYSES

The damaging affect of windblown soil particles ultimately can be related to average yield in a manner analogous to that described for depth. Of course, other criteria for damage are possible, which would affect the value of the crop and not its average yield, e.g., delay in date of maturity or perhaps visual appearance of the product. For simplicity, we shall assume some relationship to the average yield and concentrate on the factors that cause the "damage."

It is not clear from the literature what the abrasion damage measure should be. Armbrust (1968, Fig. 1) correlates the decrease in yield (as a percentage) as a function of soil loss. His soil loss measure is the mass of soil removed from the surface divided by that surface area, i.e., a surface density. No consideration is given to the time interval, except that it is implied in that the soil surface was subjected to a shear stress *until no further* motion of the soil existed. Fryrear and Downes (1975) correlate percent crop survival to various factors related primarily to the kinetic energy of the soil particle flow.

While both studies have adopted yield as their criterion, i.e., Fryrear and Downes' percent survival implied some yield, they differ as to what the measure of the erosion process should be. The variable that is the causative agent of the damage has not been defined and remains to be proven experimentally. Here we suggest a possible measure, not too far from that of Frayrear and Downes, i.e., some measure of a soil flow force intensity which, when integrated over the surface of the plant, would result in a net force.

The concept of a force related to damage is a direct carry-over from the concept of failure or damage in a structural member, such as a steel beam. Here the concept of stress and strain, as potrayed by the usual stress-strain curves, yields such terms as elastic and inelastic deformation, rupture stress, etc. (Byars et al., 1983). This concept implies that when material is subjected to a stress (a force derivative), it will change its shape, and if the stress is increased, eventually the material will fail by rupture.

While it is obvious that plant material may not have the same response to a stress, it is intuitively appealing to consider the force due to the particles as the causative agent of damage; in particular, the force per unit area or the stress at the surface of the plant. Perhaps our plant abrasion process is more analogous to failure of a metal bar by fatigue, where the applied stress is rapid and repetitive and rupture can take place well within the elastic deformation range. Our particles cause a series of impacts upon the surface of the plant, where the forces are developed when the momentum (or energy!) is transferred to the plant surface.

Whether it is a transfer of momentum or energy is not clear and, for our present purpose, it is of little concern, since as Resnick and Holliday (1966, part I, pg. 222) indicated, D'Alembert in 1743 pointed out that neither kinetic energy nor momentum was the *true* measure of the effect of a force on a body. "The cumulative effect of a force can be measured by its integrated effect over time,

$$\int F \, dt \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [26]$$

which produces a change in momentum, or by its integrated effect over space,

$$\int F \, dx \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [27]$$

which produces a change in kinetic energy. Both concepts are valid although different. Which one we use depends on what we are interested in or what is more convenient."

If we consider the various fluxes associated with particle flow, i.e., momentum, mass, and energy, we note that they differ only by a power of the particle velocity, i.e.,

$$\text{soil flux} = \rho \vec{V} = \vec{f} \, \vec{V}^0 \quad \ldots\ldots\ldots\ldots\ldots [28]$$

$$\text{momentum flux} = \rho \vec{V} \, \vec{V} = \vec{f} \, \vec{V}^1 \quad \ldots\ldots\ldots\ldots [29]$$

$$\text{energy flux} = \rho \vec{V} \, V^2 = \vec{f} \, V^2 \quad \ldots\ldots\ldots\ldots [30]$$

where we explicitly differentiate between the scalar, V^2, and the vector, $\vec{V}^n$. Consequently, in what follows, we shall refer to force or stress as the causative agent, realizing that it is a hypothesis (albeit a very reasonable one) and that the measures would only differ by a power of V.

We feel that force or, more precisely, stress is what correlates to the rupture of the plant surface and ultimately to the effect on yield. As an appeal to intuition, we offer the following analogy.

Given a rubber balloon which, when pierced, is considered damaged, and furthermore, given two probes, one sharp and the other dull, it is surmised that the sharper probe would penetrate the balloon with less applied force and with a shorter distance traveled. Consequently, we see that the energy and forces would be different but that the average stress might tend to be similar. In other words, the damage process variable becomes a property of the material rather than of the size of probe or the material. This same concept is implied in the use of a stress-strain diagram for a material whereby normalizing the force and deformation gives a single curve for material rather than a family of curves, with parameters depending on the area and length of the sample.

To indicate that the selection of a single variable to correlate to failure is not a trivial problem, we cite sections 3-10, 3-11 on failure and chapter 12, Strain and Energy and Theory of Failure, in Byars, et al. (1983). They emphasize that the selection of an appropriate damage measure, i.e., stress, strain, or energy depends on the criterion of failure. To illustrate their point, they offer a succinct example, i.e., that if a beam, which is used for bridging a stream, flexes such that a person's feet get wet, then this could be considered failure and hence the measure would be related to deformation. Certainly, the beam did not fail in the conventional sense, i.e., by rupture.

In order to develop a measure of the stress on the surface of a plant due to impacting paticles we perform a steady state momentum balance on a control volume surrounding the plant. The force of impact can be computed by integrating the momentum flux over the surface of the plant. The average force is then

$$\langle s \rangle_{S_p} \overset{\Delta}{=} \frac{\vec{F}}{\vec{S}_p} = \frac{1}{\vec{S}_p} \int_{S_p} \int \vec{V} \vec{f} \cdot d\vec{S} \quad \ldots\ldots\ldots [31]$$

assuming that we have a two-dimensional problem, i.e., f_y and V_y are zero. Then s, the stress tensor, can be decomposed into a normal and a tangential component. The normal stress would be the agent for damage by crushing, whereas the tangential or shear component would cause goughing or cutting of the plant. Obviously, any particle stream could accomplish both.

Now it might be argued that a single measure of the average stress for a total plant is not realistic, since the punctures, abrasions, tears, etc. of the surface take place on many parts of the total plant area. Consequently, damage or failure would require a definition at a lower level of surface resolution. This level of resolution can be accommodated by allowing S_p to be redefined for a portion of the total plant. Then the failure definition would be applied at this level and summed for the total plant. Now it is obvious that the time duration of the stress application will have an effect also and must be considered; however, this effect is accomplished by a time integration of a damage rate and does not add anything to the basic function that is being integrated, i.e., the momentum flux. We shall not amplify here on the methods of summing the infinitesimal damage, since it will add to our objective of the damage measure selection.

We see now that, ultimately, damage and its effect on yield can be traced to the particle momentum flux. This then would be the appropriate measure of the wind erosion process that would relate to plant abrasion damage. And if one considers the surface integral, then the average stress on the plant surface would be the appropriate measure. Since the momentum flux is related to the soil flux (equation [29]), we see that to fully describe this damage measure we must know either the particle concentration and velocity or the particle flux and velocity. Soil flux by itself is inadequate to describe damage based on the above hypothesis. Consequently, analogous to the relationship between yield and erosion, the relationship of yield to abrasion is not via W, which is a measure of the soil flux at the ground surface, $f(x,y,z_2,t)$, but to the vector product of the soil flux impinging on the plant surface $f(x,y,z,t)$ (where x,y,z are constrained to the plant surface) and the velocity at those points attributed to the particles. There is no doubt that some relationship exists between the ground surface and plant surface fluxes, but by the time they have been averaged in time, space, and statistically, it becomes difficult to determine what these relationships are and of what benefit they would be. Most likely they would even be multivalued! Consequently, it makes no sense to attempt to correlate damage by abrasion to W as has been suggested in the past.

SUMMARY

The three examples of the damaging effects of the wind erosion process and their appropriate process measures are diagrammed in Fig. 2, which shows the interrelationship between the cause and effect variables. Also illustrated is the relationship between effects and their common dependence on f and, ultimately, p and V; e.g., the path between W and h, i.e., 2 to 2′. Similar paths are shown for plant abrasion damage (3 to 3′) and productivity (1 to 1′). The appropriate functional relationships, where known, are contained in the previous sections of the paper.

CONCLUSIONS

1. The application of the conservation principles of mass, momentum, and energy, when treating particle flow as a continuum, are useful for identifying the appropriate measure for the erosion process, once the effect has been identified.

2. When the effect has been identified, it appears that its spatial (and temporal) rate of change must be determined so that (a) this rate can be integrated to give a total effect or perhaps an average value of the rate, and (b) the functional relationship of this rate to its time and spatial independent variables can be determined, e.g., Y vs. c and $c(h,B_i)$.

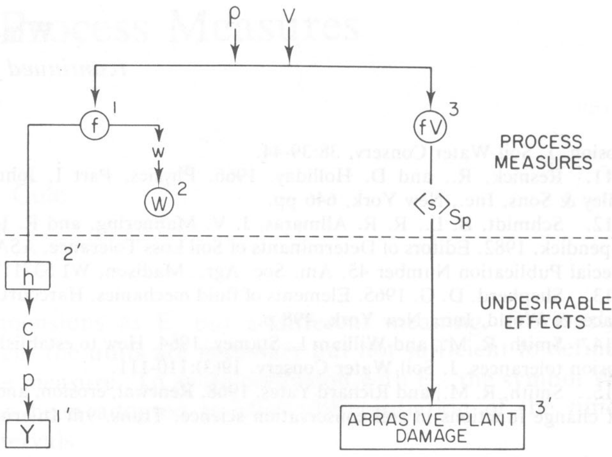

Fig. 2—The relationship between the effects of the wind erosion process and the appropriate process measures.

3. The effects of the erosion process, such as Y,h, and the plant damage for a field depend on the total plant-soil environment. Consequently, one cannot isolate any one process and determine its effect without specifying the other process measures. Also, because of the integral and average relationships implied by Y and W, a relationship between these generally is not meaningful.

4. Accepting more stringent limits on the affected variable than are necessary may simplify the selection of the process measure. For example, limiting the depth to some minimum value that guaranteed adequate productivity resulted in establishing a more manageable relationship, e.g., equation [23] vs. equation [25].

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