83-48-A

10 Wind Erosion: Processes and Prediction

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Conditions conducive to wind erosion exist when the soil is loose, dry, and finely granulated; the soil surface is smooth and vegetative cover is sparse or absent; the susceptible area is sufficiently large; and the wind is strong and turbulent enough to move soil. Those conditions often prevail in semiarid and arid climates, for example west of the 99th meridian in the USA.

The many problems researchers face in determining effects of erosion on crop productivity are represented by Fig. 10–1. A host of interactions determines crop production or yield. One way to isolate the effects of erosion in this complex crop-production system is to translate the problem from practical terms to basic concepts at the process level, where research is performed.

Even though wind erosion damages soil, crops, and the environment, we will omit any discussion of environmental damages, other than to note that future experimental research and modeling should include such impacts on crop yields. In this paper, wind erosion will be linked to productivity through its alteration of surface-soil properties and/or soil depth. This alteration must then be linked to other factors that influence the growth and development of crops.

10–1 WIND EROSION AND CROP PRODUCTION

Wind erosion is a set of processes that contribute to the motion of soil from its initiation until final deposition. Neglecting the abrasive effect of aggregate impact on crops, the interface between wind erosion and the crop-

Published in R. F. Follett and B. A. Stewart, ed. 1985. *Soil Erosion and Crop Productivity.*

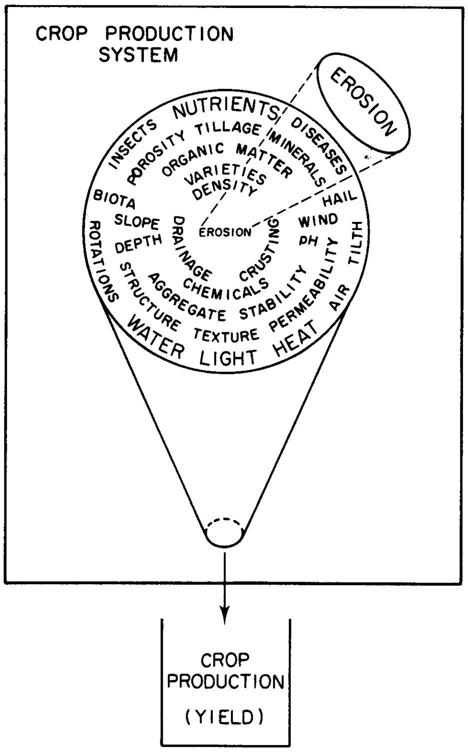

Fig. 10-1. Interacting components of the crop-production system.

production system (CPS) must be with the soil component of the CPS (Fig. 10-2). Furthermore, the soil system can only be affected by a change in soil depth, which is a measure of the size of the system, and/or a change in soil properties.

Soil properties refer to those characteristics that depend on the soil but not to any great extent on the size of a soil sample, such as, hydraulic conductivity as opposed to hydraulic conductance. This description, therefore, excludes the total soil mass of the CPS, which is a state of the system similar to the aggregate-size distribution. If the rate of soil loss exceeds the rate of soil generation, eventually the CPS will terminate and the yield will decline to zero. (The total loss is indicated by process A in Fig. 10-2). The effect of selective loss (process B in Fig. 10-2) on the CPS is not quite as obvious. To understand it, we must consider both wind erosion and the soil system.

The literature indicates that some soil properties can be correlated directly to the primary particle-size distribution (PSD) (Gupta and Larson, 1979; Arya and Paris, 1981). Because wind erosion is generally a selective soil-loss process, which moves aggregates of various size fractions at different mass-flow rates (Chepil, 1951), one also needs to understand how the aggregate-size distribution (ASD) is related to soil properties. Selective soil loss appears to be linked to soil properties primarily through the ASD

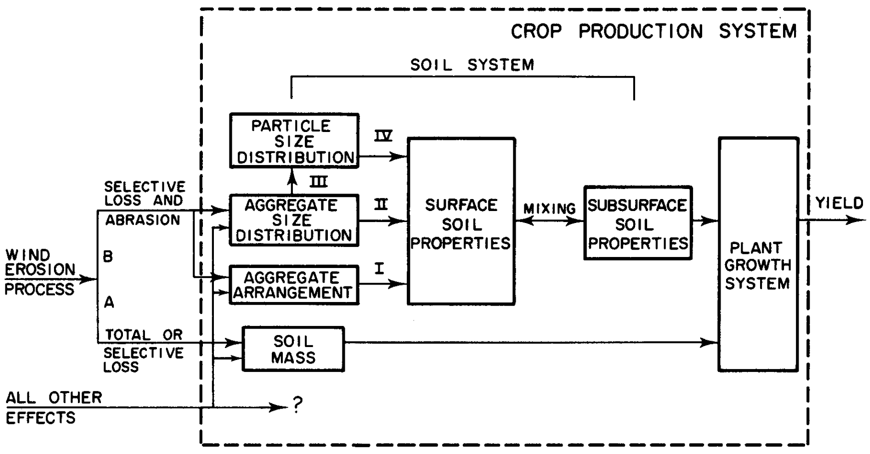

Fig. 10–2. The wind-erosion process and its interface with the crop-production system.

and the PSD. This linkage is illustrated in Fig. 10–2 as lines II, III, and IV, which represent functional relationships. Line III suggests that a change in ASD due to abrasion and sorting may affect the PSD as well. In general, when the aggregates are not homogeneous with respect to their PSD's, this path will exist. Line IV, between PSD and surface-soil properties, is that cited previously. Line II, between ASD and surface-soil properties, indicates the effect on properties associated with fluid and energy transport through the surface, such as gas and liquid permeabilities. Except for fluid and energy transport properties, all these effects occur at or near the soil surface. Unless these effects are extended to subsurface layers, the plant-growth system will be relatively unaffected. Unfortunately, soil mixing accomplishes this extension.

The spatial arrangement of surface aggregates, of which nothing quantitative is known at present, also affects surface-soil properties (line I, Fig. 10–2). Aggregate arrangement can also affect soil loss by sheltering the smaller aggregates. Other factors, such as water erosion, tillage, and weather, also affect the same variables that are affected by wind erosion and are included in Fig. 10–2 as "all other effects."

10–2 WIND EROSION PROCESSES

The most comprehensive summaries on the movement of surface material by wind action have been prepared by Bagnold (1941) for desert sands and by Chepil and Woodruff (1963) for agricultural lands. Wind erosion consists of initiation, transport (suspension, saltation, surface creep), abrasion, sorting, avalanching, and finally deposition of soil aggregates/particles (A/P). We will limit our viewpoint here to periods when erosion is actually occurring. Soil transport by wind is commonly described in three distinct modes: suspension, saltation, and surface creep.

10–2.1 Suspension

Suspension refers to the vertical and (eventual) horizontal transport of A/P that are generally removed from the local source area. Chepil (1945) reported that 3 to 38% of total transport could be carried in suspension, depending on soil texture. Generally, the vertical transport is less than 10% of the horizontal (Gillette, 1977 and 1978). Suspendible A/P's range in size from 2 to 100 μm in diameter, with a mass median diameter of about 50 μm in an actively eroding field (Chepil, 1957a; Gillette and Walker, 1977). This size range excludes the fine, medium, coarse, and very coarse sand particles and aggregates of corresponding size, which remain in the local area. Because organic matter and some plant nutrients are usually associated with the finer soil fractions, suspension samples are enriched in such constituents compared with the bulk soil source. Furthermore, the enrichment ratio increases as the amount of sand particles too large to be suspended by common winds increases in the bulk soil. Consequently, suspension indirectly impacts productivity through removal of organic matter and plant nutrients or, conversely, by leaving behind the less-fertile soil constituents. It directly affects the surface-layer ASD during erosion, but, as previously noted, ASD in the new surface layer, depending on PSD, may be unchanged when erosion ceases.

Because of our present definition of the wind-erosion process, we exclude subsequent deposition of suspension-sized A/P's. On an expanded treatment of wind-erosion processes, deposition contributes to soil renewal (Smith et al., 1970) and might even need to be included in determining the effects of erosion on crop productivity.

10–2.2 Saltation

The characteristics of saltation (jumping) A/P's in wind have been described (Bagnold, 1941; Chepil, 1945; Free, 1911; White and Schultz, 1977). Roughly 50 to 80% of total wind transport is by saltation. During saltation, individual A/P's lift off the surface (eject) at 50 to 90° angles, rotate at 115 to 1000 r/s, and follow distinctive trajectories under the influence of air resistance and gravity (Chepil, 1945; White and Schulz, 1977). Those A/P's 100 to 500 μm in diameter (too large to be suspended by the flow) return to the surface at impact angles of 6 to 14° from the horizontal, either to rebound or to embed themselves, thus influencing the breakdown and movement of other A/P's. The size range for saltation excludes the coarse and very coarse sand particles, which remain in the local area. During erosion, saltating aggregates may shift to the suspension mode because of abrasion and may cause other aggregates at the surface to shift modes. Saltation is the major cause of aggregate breakdown during erosion. Its role is to initiate and sustain suspension, drive the creep transport, and influence ASD of the soil surface. Therefore, linkage through those factors must be established to determine the impact of saltation on crop productivity. As with suspension, ASD in the new surface layer may be unchanged when erosion ceases.

10–2.3 Surface Creep

Coarse, sand-sized, mineral-soil A/P's 500 to 1000 μm in diameter, too large to leave the surface in ordinary erosive winds, can be set in motion by the impact of saltating A/P's. Reportedly, surface creep constitutes 7 to 25% of total transport (Bagnold, 1941; Chepil, 1945; Horikowa and Shen, 1960). In high winds, the entire surface appears to be creeping slowly forward at speeds much less than 2.5 cm/s pushed and rolled (driven) by the saltation flow. Surface creep normally excludes very coarse sand particles and gravels greater than 2000 μm in diameter which, if contained in the bulk soil, must remain near their current location during wind erosion. Creep appears nearly passive in the erosion process, but creep-sized aggregates may abrade into the size ranges of saltation and suspension and thus shift modes of transport. The impact of surface creep on productivity appears to be linked primarily to ASD effects.

10–2.4 Abrasion

Many aggregation and deaggregation processes affect the soil-surface layer between erosion events. These processes generally produce log-normal, surface soil ASD's (Gardner, 1956). The log-normal distributions often approach limits at the extremes, however, because the maximum size of the aggregates may be controlled by processes such as tillage, and the minimum aggregate size may be controlled by the size of the primary particles themselves, which usually do not have log-normal distributions. Suspension of the particles less than 100 μm in diameter during wind erosion may also change the lower limit of the surface ASD.

The percentage of erodible soil (i.e., less than 1000 μm in diameter) in the surface layer is highly correlated with the mass of soil one can remove from that surface in wind-tunnel tests (Chepil, 1958). On long fields, the amount of soil that passes from a control volume on the soil surface because of saltation and creep increases nearly linearly with field length (Chepil, 1957b). Such a result implies abrasive breakdown of both erodible and nonerodible aggregates. Indeed, on long, erosion-susceptible fields, the total amount of soil that can be lost is usually several times the amount of erodible material initially present at the surface. Thus, both initial ASD and resistance to abrasive breakdown of surface aggregates are important in wind erosion.

An abrasion susceptibility term (w) can be defined as the mass of material abraded from target aggregates per unit mass of impacting abrader. To determine how various factors affect w, large soil aggregates (50–100 mm in diameter) have been abraded with sand particles and soil aggregates using a calibrated nozzle (Hagen, 1984). The results show that

$$w = f(V_a, \alpha, d_a, S_t, S_a, \varrho_a) \quad [1]$$

where V_a is the average velocity of the impacting A/P's; α is the A/P impact angle with the surface plane; d_a is the average diameter of abrading A/P's; S_t and S_a are dry mechanical stabilities of the target aggregates and abrading aggregates, respectively; and ϱ_a is the A/P density of the abrader. Aggregate abrasion affects the soil system through ASD and aggregate arrangement (Fig. 10–2).

10–2.5 Sorting

Unless surface-layer A/P's are homogeneous in physical properties (size, shape, density), which is highly unlikely in agricultural soils, sorting will occur during erosion. Sorting here refers to the selective removal during erosion of A/P's, because various sizes move at different mass-flow rates. The impact of sorting on crop productivity would ultimately be expressed through changes in ASD associated with discrete erosion events. Changes in ASD are contingent on initial PSD and ASD, homogeneity with depth, aggregate stability, erosive wind duration, presence or absence of erosion-resistant "layers", and arrangement of nonerodible aggregates with depth. In most cases envisioned, ASD would change during discrete erosion events. The most common case where ASD would remain the same would involve A/P homogenity with depth, no particles greater than 1000 μm in diameter, an erosion-resistant layer below the soil surface caused by binding agent(s) or water, and all the A/P's above the resistant layer being removed by the erosion event.

10–2.6 Process Alteration

In general, wind erosion can be decreased only by reducing wind forces on erodible A/P's or by creating aggregates or surfaces more resistant to wind forces. Nonerodible elements reduce wind-drag forces on erodible A/P's (Fig. 10–3). Various components of the erosion process might be altered by reducing field length, increasing dry-aggregate stability, changing ASD, altering the path of the wind, providing trapping surfaces, or reducing wind forces.

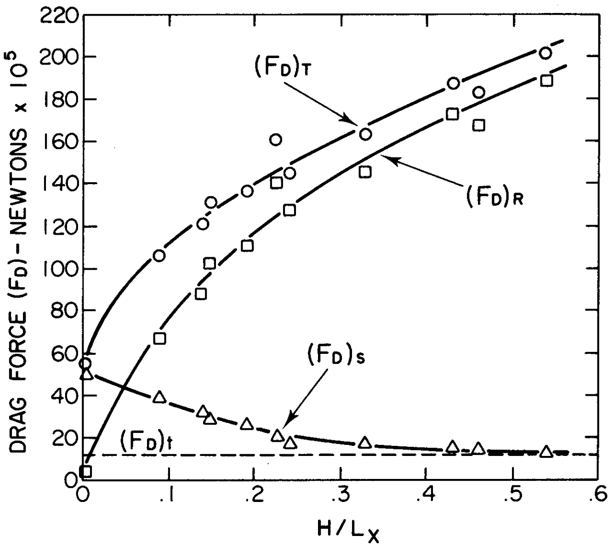

Fig. 10-3. How wind drag (F_D) changes as an eroding surface stabilizes by exposing nonerodible elements. Subscripts T, R, S, and t refer to total drag forces, drag forces on the nonerodible roughness elements, drag forces on the intervening surface, and threshold drag of erodible aggregates/particles, respectively. H is height and L_x is downwind distance between nonerodible elements (adapted from Lyles et al., 1974).

10-3 PREDICTION OF WIND EROSION

10-3.1 Present Methods

Currently, prediction of wind erosion is largely associated with the wind-erosion equation (WEE) originally reported by Woodruff and Siddoway (1965):

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

where E is the potential annual soil-loss flux, I is the soil erodibility, K is the soil-ridge-roughness factor, C is the climatic factor, L is the unsheltered "weighted" distance that wind travels across a field, and V is the equivalent vegetative cover. Cole et al. (1982) discussed two "weighting" methods that have been used to determine L, and Skidmore (unpublished data) has proposed another.

Procedures have been developed for applying Eq. [2] to periods shorter than 1 year, which involves partitioning erosion amounts over time with erosive wind-energy distribution as the criterion (Bondy et al., 1980). Recently, a similar approach has been used in Erosion-Productivity Impact Calculator (EPIC) (Williams et al., 1984), which operates on a daily time step. Details of the daily, wind-erosion, soil-loss model have been reported by Cole et al. (1982).

Regardless of the modifications, the E term in WEE predicts only total soil removal. Hence, it can be viewed only in terms of accumulated loss of topsoil depth when applied to the problem of determining erosion effects on crop productivity.

10–3.2 Future Methods

Classically, prediction of wind erosion has been linked to the idea that any soil loss is bad and that the appropriate measure of "badness" is the potential average, annual, soil loss (E). Because of the soil erosion/crop productivity problem, however, the measure must now be expanded to include wind-erosion effects on surface-soil properties. This is represented in Fig. 10–2 as the wind-erosion processes of sorting and abrasion, which affect ASD. A relationship between E and ASD is also implied in Fig. 10–4, where a mass balance model is depicted for n soil-size classes. Also shown are two ASD's, representing possible initial and final states of the surface-soil mass.

The final ASD of Fig. 10–4 represents the solution generated by the model after running for a specified time, having started with the condition implied by the initial ASD. Therefore, given the initial state of the system and a description (i.e., equations) of the soil-loss ratios ($\dot{m}_i$) and abrasion rates ($\dot{a}_i$), the final ASD is predictable.

Because the model illustrated is for a field of size A, E could be computed by taking the average sum over time of all $\dot{m}_i$ and dividing by A. Hence, the information needed to generate our present soil-loss measure is

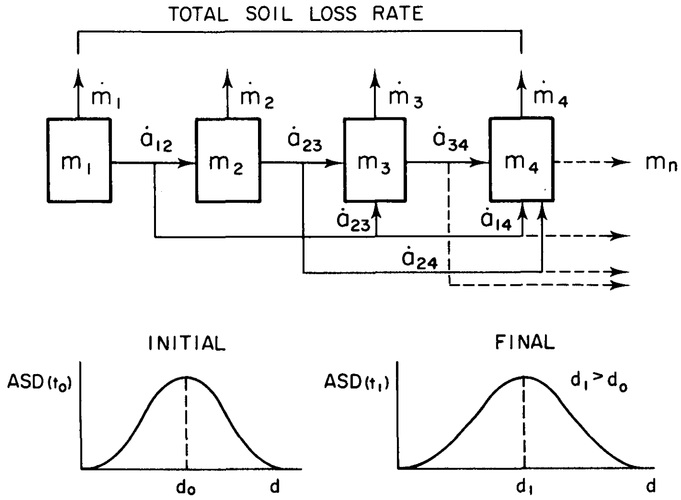

Fig. 10–4. Soil transport-abrasion model for an homogeneous field surface, in which $\dot{m}_i$ and $\dot{a}_{ij}$ are mass soil-loss rates and abrasion rates by aggregate/particle size class, respectively.

inherent in this new model. Another way to view the relationship between Fig. 10–4 and E is simply to lump all the $\dot{m}_i$ compartments into one. All the lines representing the abrasion process thus disappear, and the sum of $\dot{m}_i$ becomes $\dot{m}_{total}$, which relates to E as previously noted.

Probably of more significance in the new model than the inclusion of abrasion rates is that we are now interested in the resulting state of that portion of the system that is *not* lost. This contrasts with predicting E, which says nothing about what remains behind in a given size class. Although the abrasion rates were not previously required, they must be included here because we now need to predict the final ASD and because abrasion is the only other wind erosion process that affects the ASD.

Clearly, Fig. 10–4 represents an expanded model capable of predicting both ASD and E, although this new model requires equations for $\dot{m}_i$ and $\dot{a}_i$ which, unfortunately, are unknown at present. Obviously, for prediction of ASD, development of such equations is required.

10–4 FUTURE RESEARCH

As indicated previously, Fig. 10–2 portrays the wind-erosion processes and fundamental relationships involved in changing soil properties and size distributions. In particular, the crucial processes for describing wind-erosion effects on the CPS are labeled A and B, and the functional relationships, which are not unique to the wind-erosion process, are labeled I to IV. The distinction between processes and functions provides a clear image of the direction of future research. For example, part of process A represents the state-of-the-art of wind-erosion research: prediction of the total average soil-loss flux. However, the subdivision of the soil-loss flux by aggregate-size class has not yet been accomplished (except for rough generalizations among transport modes). That subdivision, in conjunction with abrasion rates by size class, will be required to describe process B. Both of the above involve field, wind-tunnel, and theoretical studies.

In contrast, functional relationships I and II do not involve the processes of wind erosion. They are in the domain of soil physics and are independent of the process that caused the ASD or aggregate arrangement to change. Relationship IV is being studied. Relationship III is proposed for future study because it is an important link in interactions between wind erosion and the crop-production system.

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