Physics of desertification

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SOIL EROSION BY WIND: AN OVERVIEW

By

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ABSTRACT

Wind erosion is a serious problem in many parts of the world. It physically removes the most fertile portion of the soil from the field, pollutes the air, fills road ditches, reduces seedling survival and growth, and lowers the marketability of many vegetable crops. Wind erosion also creates new desert landforms and landscapes.

Wind erosion is generally worse in arid and semiarid climates. It can be a problem wherever soil, vegetative, and climatic conditions are conducive.

Soil particles erode when shear stress exerted by the wind against the ground surface exceeds the forces tending to hold the particles in place. The eroding particles may be transported in saltation, creep, or suspension.

Principles for controlling wind erosion include: stabilizing with various materials; producing a rough, cloudy surface; reducing field width with strips and barriers; and establishing and maintaining sufficient vegetative cover.

PROBLEM

Lands undergoing desertification become vulnerable to wind erosion (Secretariat, 1977, p. 14). In pastoral rangelands, composition of pastures subject to excessive grazing in dry periods deteriorates, the proportion of edible perennial plants decreases, and the proportion of annuals increases. The thinning and death of vegetation in dry seasons or droughts increases the extent of bare ground. The surface soil conditions deteriorate. In rain-fed farming, removal of the original vegetation and fallow expose the soil to accelerated wind and water erosion.

Wind erosion is worse in arid and semiarid areas where the conditions conducive to wind erosion frequently occur. Those conditions are: (1) loose, dry, finely divided soil; (2) smooth soil surface devoid of vegetative cover; (3) large fields; and (4) strong winds (FAO, 1960).

The arid lands are extensive, comprising about one-third of the world's population (Dregne, 1976; Gore, 1979). The general areas most susceptible to wind erosion on agricultural land are much of North Africa and the Near East, parts of southern and eastern Asia, Siberian Plain, Australia and southern South America, and the semiarid and arid portions of North America (FAO, 1960).

Extensive soil erosion in the Great Plains, USA, during the last half of the 19th century and the 1920's in the prairie region of western Canada gave warning of impending disaster, and during the 1930's a prolonged dry spell culminated in dust storms and soil destruction of disastrous proportions of the prairie regions of both western Canada and the Great Plains of the United States (Anderson, 1975; Svobida, 1940; Malin, 1946a, b, c; Johnson, 1947).

Wind erosion physically removes the most fertile portion of the soil from the field and therefore lowers productivity of the land (Daniel and Langham, 1936; Lyles, 1975).

Some soil from damaged lands enters suspension and becomes part of the atmospheric dustload. Hagen and Woodruff (1973) estimated that eroding lands of the Great Plains contributed 244 and 77 million tons of dust per year to the atmosphere in the 1950's and 1960's, respectively. Jaenicke (1979) estimated the source strength of mineral dust from the Sahara at 260 million tons per year. Dust obscures visibility and pollutes the air, causes automobile accidents, fouls machinery, and irritates the housewife.

Blowing soil fills road ditches, reduces seedling survival and growth, lowers the marketability of vegetable crops like asparagus, green beans, and lettuce, and increases the susceptibility and transmission of some diseases (Hayes, 1965, 1966; Claflin, Stuteville, and Armbrust, 1973).

MECHANICS

Surface Wind. Movement of soil particles is caused by wind forces exerted against the surface of the ground. The average forward velocity of the wind near the ground increases exponentially with height above the ground surface. The change in velocity with height is known as the velocity gradient. It is this gradient that determines the shear stress or drag force exerted on the ground surface.

The velocity gradient or the shape of the adiabatic windspeed profile is given by

$$\frac{\partial u}{\partial z} = \frac{u_*}{kz} \qquad (1)$$

where u is mean windspeed at height z above the mean ground surface, k is the von Karman constant (0.4); and u_* is friction velocity further defined as $(\tau/\rho)^{1/2}$ where τ is surface shear (force per unit area) and ρ is fluid density. The surface shear then is

$$\tau = \rho u_*^2. \qquad (2)$$

The surface shear associated with the decrease in wind velocity as the surface is approached is a vertical transfer of horizontal momentum. Momentum (the product of mass and velocity) decreases as the surface is approached. The eddy diffusion equation for steady state one-dimensional transport is

$$\tau = \rho K_m \ \partial u/\partial z \qquad (3)$$

where Km is momentum transfer coefficient. The integrated form of equation 1 over a rough surface becomes

$$u = \frac{u_*}{k} \ell n \frac{z - z_d}{z_o}. \qquad (4)$$

The parameter z_d, the effective displacement height, is the distance from the ground surface to the plane at which the momentum exchange coefficient extrapolates to zero. Roughness parameter, z_o, is the distance from the displaced reference plane to the surface at which the wind profile extrapolates to zero.

Equilibrium Forces. In addition to surface shear, another force tending to dislodge a soil grain is a negative pressure on the top as compared to the bottom of the grain. This Bernoulli effect causes lift on the grain (Chepil, 1959).

Chepil (1959) analyzed the nature of forces of drag, lift, and gravity on soil grains at the threshold of their movement by wind. He found that equilibrium between these forces and the soil grains was influenced by the diameter, shape, and density of the grains, the angle of repose of the grains with respect to the mean drag level of the fluid, the closeness of packing of top grains, and the impulses of fluid turbulence associated with drage and lift. The relationship was

$$\overline{\tau}_c = 0.66\ g d \rho \tan \phi n/(1 + 0.85 \tan \phi)T \quad (5)$$

where $\overline{\tau}_c$ is the mean critical drag per unit horizontal area, g is acceleration of gravity, d is diameter of spherical grain, is difference in density of grain and fluid, ϕ is angle of repose of the grain with respect to the mean drag level of the fluid, n is ratio of mean drag and lift per unit area to mean drag and lift per unit area on the top grain moved by the fluid, T is the ratio of maximum to mean drag and lift on the soil grain. Chepil (1959) experimentally determined the following values for the constants of equation 5: T = 2.5, tan ϕ = 0.45, and n = 0.21.

When the mean critical drag on a particle is exceeded, the particle dislodges and is transported by the wind. This occurs for loose grains with 0.25 mm diameter when the friction velocity u_* is 20 to 44 cm/sec (Lyles and Krauss, 1971; Chepil, 1959; Zingg, 1953; Bagnold, 1943), which corresponds to surface drag of 0.48 to 1.94 dynes/cm^2. The windspeed at initial particle movement is from 4.0 to 5.8 m/sec at 30 cm (Chepil, 1945b, c; Malina, 1941).

Initial Particle Motion. The windspeed at which sand movement starts, due to the direct pressure of the fluid was called "fluid threshold" by Bagnold (1943). Bagnold described the initial motion as "surface grains, previously at rest, began to be rolled along the surface by the direct pressure of the wind... A foot or so downwind of the point at which the rolling began, the grains could be seen to have gathered sufficient speed to start bouncing off the ground." Others (Bisal and Nielsen, 1962; Lyles and Krauss, 1971) observed that as the fluid threshold was approached, some particles began to vibrate, or rock back and forth. Erosive particles vibrated with increasing intensity as windspeed increased and then left the surface instantaneously as if ejected. Evidence supported the hypothesis that the particle-vibration frequency is related to the frequency band containing the maximum energy of the turbulent motion.

Saltation. The bouncing or ejection of the eroding particle off the surface bed into the airstream and subsequent forward movement is referred to as saltation. Fifty to 75 percent of the movement of soil particles takes place through saltation (Chepil, 1945a). In saltation the particles rise almost vertically, rotating from 20 to 1,000 revolutions per second, travel 10 to 15 times their height of rise, and return to the surface with an angle of descent of about 6 to 12 degrees from the horizontal (Chepil and Woodruff, 1963). On striking the surface they either rebound and continue their movement in saltation or impart most of their energy by striking other grains, causing these to rise upward or roll along the surface. Most of the saltating particles range in size from 0.1 and 0.5 mm in diameter.

Creep. The rolling or sliding or larger particles with energy derived from saltating particles is called creep. Individual grains are knocked onward by the blow they receive from behind. Bagnold (1943) observed that at low windspeeds the grains move in jerks a few millimeters at a time, but as windspeed increases, the distance moved lengthens and more grains are set in continuous motion until in high winds the whole surface appears to be creeping forward.

Suspension. Particles smaller than about 0.1 mm may enter suspension and be carried to great heights by the eddies of the erosive winds. Movement of these fine particles is usually initiated by the impact of particles in saltation. The greatest amount of soil is moved by saltation and surface creep but that moved by suspension is the most spectacular and easily recognized from a distance.

Sorting. An eroding wind has been said to act on the soil like a fanning mill on grain, removing the finer and more porous particles and leaving the coarser and denser behind (Chepil, 1957a; Moss, 1935; Daniel, 1936). The coarser eroded material usually ends up in a soil drift whereas the finer enters suspension and is transported often times great distances before deposition. Chepil (1957a) observed that the most distinct feature in the sorting process was that the particles of peak diameter tend to remain in the wind-eroded fields, and particles smaller than this diameter tend to be carried far through the atmosphere in suspension.

Peak diameter of drifted material derived from fields composed of sand and loamy sand was about 0.4 mm, and that of drifted material from the finer-textured soils was about 0.6 mm. The drifted materials derived from fields of sand and loamy sand were composed principally of discrete, nonporous grains having an average bulk density of 2.37, whereas the materials drifted from the finer-textured soils were predominantly aggregates exhibiting a distinct degree of porosity and having an average bulk density of 1.70 (Chepil, 1957a).

By applying equation 5 for peak diameters and average bulk densities, I found that critical mean drag is about the same for both conditions; 1.7 and 1.8 dynes/cm^2 for the single grain and porous grains, respectively.

Very little sorting occurs on fine-textured soil derived from loess. Moss (1935) found that clay soils and the corresponding drifted materials were practically identical in composition. In some cases, wind erosion virtually removes the surface soil (Zingg, 1954; Chepil, 1957a, b). This nonselective removal by wind is associated primarily with loess which was already sorted and deposited from the atmosphere during past geologic eras.

CONTROL PRINCIPLES

Principles for controlling wind erosion include: stabilizing with various materials; producing a rough, cloddy surface; reducing effective field width with barriers; and establishing and maintaining sufficient vegetative cover.

Stabilizers. Various soil stabilizers have been evaluated to find suitable materials and methods to control wind erosion (Armbrust and Dickerson, 1971; Armbrust and Lyles, 1975; Chepil, 1955; Chepil and Woodruff, 1963; Chepil et al., 1963; Lyles et al., 1969; Lyles et al., 1974). Several tested products successfully controlled wind erosion for short periods of time but were often expensive as compared with equally effective wheat straw anchored with a rolling disk packer (Chepil et al., 1963). The following are criteria for surface soil stabilizers; (1) 100 percent of the soil surface must be covered, (2) the stabilizer must not adversely affect plant growth or emergence, (3) erosion must be prevented initially and reduced for at least 2 months, (4) the stabilizer should apply easily and without special equipment, and (5) cost must be low enough for profitable use (Armbrust and Lyles, 1975). Armbrust and Lyles (1975) found five polymers and one resin-in-water emulsion that met all those requirements. However, they added that before soil stabilizers can be used on agricultural lands, methods must be developed to apply large volumes rapidly. Also, reliable preemergent weed control chemicals to use on coarse-textured soils must be developed, as well as films resistant to raindrop impact, yet still allow water and plant penetration without adversely affecting the environment.

Rough, Cloddy Surface. Chepil and Milne (1941a), investigating the influence of drifting dune materials and cultivated soils found that the initial intensity of drifting was always much less over a ridged surface. Ridging cultivated soils reduced the severity of drifting, but ridging highly erosive dune materials was less effective because the ridges disappeared rapidly. The rate of flow varied inversely with surface roughness.

Armbrust et al. (1964) studied the effects of ridge roughness equivalent on total quantity of eroded material from three simulated, cultivated soils exposed to different friction velocities. From their data, a curve can be constructed showing the relationship between quantity of eroded material and ridge roughness equivalent. Presumably, this was the origin of the chart (Woodruff and Siddoway, Figure 4, 1965) showing a soil ridge roughness factor as a function of soil ridge roughness so that a ridge roughness equivalent of 6 cm reduces wind erosion 50 percent. As roughness increases to about 11 cm, the soil ridge roughness factor remains about contant, then with additional roughness, the effectiveness of ridges gradually decreases.

When ridges are mostly gone, vegetative cover is depleted, and the threat of wind erosion continues, a rough, cloddy surface resistant to the force of wind can be created on many cohesive soils with appropriate "emergency tillage." Listers, cultivators, one-ways with two or three disks removed at intervals, and pitting machines can be used to bring compact clods to the surface. Emergency tillage is most effective when done at right angles to the prevailing wind direction. Since the clods eventually disintegrate (sometimes rapidly), emergency tillage offers, at best, only temporary wind erosion control (Woodruff et al., 1957).

Residue. Living vegetation or residue from harvested crops protects the soil against wind erosion. Standing crop residues provide nonerodible elements that absorb much of the shear stress in the boundary layer. When vegetation and crop residues are sufficiently high and dense to prevent intervening soil surface drag from exceeding threshold drag, soil will not erode. Rows perpendicular to wind direction control wind erosion more effectively than rows parallel to wind direction (Englehorn et al., 1952; Skidmore et al., 1966). Flattened stubble, though not as effective has standing, also protects the soil from wind erosion (Chepil et al., 1955).

Studies (Chepil, 1944; Chepil et al., 1955; Siddoway et al., 1965) to quantify specific properties of vegetative covers influencing wind erosion led to the relationship presented by Woodruff and Siddoway (1965) showing the influence of an equivalent vegetative cover of small grain and sorghum stubble for various orientations (flat, standing, height).

Efforts have continued to evaluate the protective role of additional crops (Craig and Turelle, 1964; Lyles and Allison, 1981), range grasses (Lyles and Allison, 1980), feedlot manure (Woodruff et al., 1974), and the protective requirements of equivalent residue needed to control wind erosion (Skidmore and Siddoway, 1978; Skidmore et al., 1979).

Barrier. Reducing the field width or the distance that wind travels in crossing the field reduces wind erosion. Chepil and Milne (1941b) reported that the rate of soil movement began with zero on the windward side of fields or field strips and increased with distance downwind. Later Chepil (1946) found that the cumulative rate of soil movement with distance away from the windward edge of eroding fields was the main cause of increasing abrasion and gradual decrease in surface roughness along the direction of the wind. He called the increase in rate of flow with distance downwind "avalanching."

"Rate of soil flow increased with distance downwind across an eroding field until, if the field was large enough, it reached a maximum that a wind of a given velocity can carry. Beyond that point the rate of flow remained essentially constant"--(Chepil, 1957c).

Use of wind barriers is an effective method of reducing field width. Barriers have long been recognized as valuable for controlling wind erosion (Bates, 1911). Hagen (1976) and Skidmore and Hagen (1977) have presented a model which, when used with local wind data, showed wind-barrier effectiveness in reducing wind erosion forces: Barriers reduce wind forces more than they do windspeed; a properly oriented barriers, when winds predominate from a single direction, will decrease wind erosion forces by more than 50 percent from the barrier leeward to 20 times its height; the decrease is greater for shorter distances from the barrier.

Different combinations of trees, shrubs, tall growing crops, and grasses can reduce wind erosion. Besides the more conventional tree windbreak (Ferber, 1969; Read, 1964; Woodruff et al., 1976), many other barrier systems are used to control wind erosion including annual crops like small grains, corn, sorghum, sudangrass, sunflowers (Carreker, 1966; Fryrear, 1963, 1969; Hagen et al., 1972; Hoag and Geiszler, 1971), tall wheatgrass (Aase et al., 1976; Black and Siddoway, 1971), sugarcane, and rye strips on sands in Florida (Griffin, SCS Agronomist, personal communication, 1975).

However, most barrier systems for controlling wind erosion occupy space that could otherwise be used to produce crops. Perennial barriers grow slowly and are often established with difficulty (Dickerson et al., 1976; Woodruff et al, 1976). These barriers also compete with the crop for water and plant nutrients. Thus, the net effect for many tree barrier systems is that production may not be benefited from their use (Frank et al., 1977; McMartin et al., 1974; Skidmore et al., 1975; Skidmore et al., 1974; Staple and Lehane, 1955). Perhaps, the tree-barrier systems could be designed so that they become a useful crop, furnishing nuts, fruit and wood.

Strip cropping. The practice of farming land in narrow strips on which the crop alternates with fallow is an effective aid in controlling wind erosion. Strips are most effective when they are at right angles to the prevailing wind erosion direction but also provide some protection from winds that are not perpendicular to the strip. Strip cropping reduces wind erosion damage in the following ways: it reduces the distance the wind travels across exposed soil; localizes drifting that starts at a focal point; and reduces wind velocity across the strip when adjacent fields are covered with tall stubble or crops.

Although each method to control wind erosion has merit and application, when feasible, establishing and maintaining vegetative cover remains the best defense against wind erosion. However, this becomes a difficult challenge as pressure increases to use the crop residues for livestock feed and fuel for cooking.

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