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ENCYCLOPEDIA OF EARTH SCIENCES, VOLUME XII

# The ENCYCLOPEDIA of SOIL SCIENCE PART 1

## Physics, Chemistry, Biology, Fertility, and Technology


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## WIND EROSION

Although soil erosion by wind is generally believed to be of consequence only in semiarid and arid areas, it can be a problem wherever soil, vegetative, and climatic conditions are conducive (FAO, 1960). These conditions exist when: (1) The soil is loose, dry, and reasonably finely divided; (2) the soil surface is smooth and vegetative cover is absent or sparse; (3) the field is sufficiently large; and (4) the wind is sufficiently strong to move soil. Those conditions more often prevail in semiarid and arid areas where precipitation is inadequate or where the vagaries from season to season or year to year prevent maintenance of crops or residue cover on the land, but they are sometimes present in subhumid, and sometimes even humid, areas.

General areas most susceptible to wind erosion on agricultural land include much of North Africa and the Near East, parts of southern and eastern Asia, Australia and southern South America, and the semiarid and arid portions of North America [Food and Agricultural Organization of the United Nations (FAO), 1960]. In addition, such agricultural areas as the Siberian Plain and others in the USSR have a potential for wind erosion.

Wind erosion is the dominant problem on about 30 million hectares of land in the United States (U.S. Department of Agriculture, 1965). About 2 million hectares are moderately to severely damaged each year. Extensive soil erosion during the last half of the nineteenth century in the Great Plains of the United States and during the 1920s in the prairie region of western Canada gave warning of impending disaster; during the 1930s a prolonged dry spell culminated in dust storms and soil destruction of disastrous proportions in the prairie regions of western Canada and the Great Plains of the United States (Anderson, 1975; Johnson, 1947; Malin, 1946*a,b,c;* Svobida, 1940).

Wind erosion physically removes from the field the most fertile portion of the soil and therefore lowers productivity (Daniel and Langham, 1936). By relating crop yield to soil thickness and determining potential annual soil loss, Lyles (1975) estimated annual yield reductions of 9.2 thousand tons (metric) of wheat and of 13.8 thousand tons (metric) of grain sorghum on 0.5 million hectares of sandy surface soils in southwestern Kansas.

Some soil from damaged lands enters suspension and becomes part of the atmospheric dustload (Figure 1). 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 1950s and 1960s, respectively. Dust obscures visibility and pollutes the air, causes traffic hazards, fouls machinery, and imperils animal and human health. 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 to and transmission of some diseases (Claflin, Stuteville, and Armbrust, 1973; Hayes, 1965, 1966). Extent of damage and plant response to windblown soil-abrasive injuries have been evaluated for several crops: winter wheat (Armbrust, Paulsen, and Ellis, 1974; Woodruff, 1956); green beans (Bubenzer and Weis, 1974; Skidmore, 1966); cotton (Armbrust, 1968; Fryrear, 1971); soybean (Armbrust, 1972); tomato (Greig et al, 1974); peas Bubenzer and Weis, 1974); and alfalfa and various grasses (Lyles and Woodruff, 1960). These crops differ in susceptibility to soil-abrasive injuries.

FIGURE 1. Some soil from eroding fields enters suspension and becomes part of the atmospheric dustload. The suspended dust obscures visibility and pollutes the air.

## Erosion 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 logarithmically with height above the ground surface (Figure 2). The change in velocity with height is known as the *velocity gradient.* This gradient determines the shear stress of 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 $\tau$ is surface shear (force per unit area), and $\rho$ is fluid density. The surface shear then is

$$\tau = \rho u^{*2} \qquad (2)$$

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

$$\tau = \rho\, Km \frac{\partial u}{\partial z} \qquad (3)$$

where $Km$ is momentum-transfer coefficient.

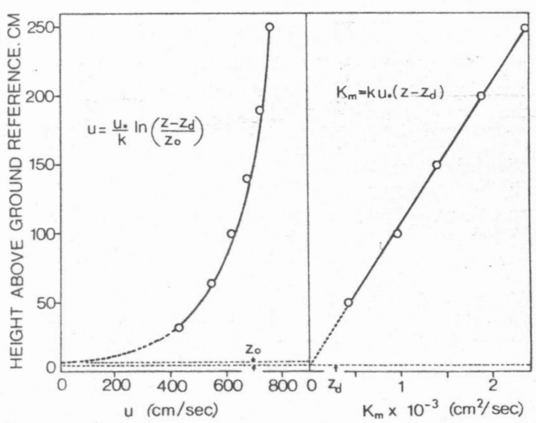


FIGURE 2. Measured windspeed $u$ and calculated transfer coefficient Km profiles over ground surface where $z_0$, $z_d$, and u* were calculated to be 1.6 cm, 5.8 cm, and 60 cm/s, respectively.

The integrated form of equation 1 over a rough surface becomes

$$u = \frac{u^*}{k} \ln\left(\frac{z - z_d}{z_0}\right) \qquad (4)$$

which is the well-known logarithmic law. The parameter $z_d$, the effective displacement height, is the distance from the ground surface to the plane at which the momentum-transfer coefficient extrapolates to zero (Figure 2). The roughness parameter $z_0$ 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 with the bottom of the grain. This Bernoulli effect causes lift on the grain (Chepil, 1959*b*). Chepil (1959*b*) analyzed the drag, lift, and gravity forces on soil grains at the threshold of their movement by wind. Equilibrium between those 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 drag and lift. The relationship was

$$\overline{\tau}_c = \frac{0.66\, g d \rho' \tan \phi \eta}{(1 + 0.85 \tan \phi)\, T} \qquad (5)$$

where $\overline{\tau}_c$ is the mean critical drag per unit horizontal area of the whole bed; $g$ is acceleration of gravity; $d$ is diameter of the spherical grain; $\rho'$ is difference in density of grain and fluid; $\phi$ is angle of repose of the grain with respect to the mean drag level of the fluid; $\eta$ is ratio of mean drag and lift per unit area on the whole bed to mean drag and lift per unit area on the top grain moved by the fluid; and $T$ is the ratio of maximum to mean drag and lift on the soil grain. Chepil (1959*b*) experimentally determined these values for the constants of equation (5): $T = 2.5$, $\tan \phi = 0.45$, and $\eta = 0.21$. Lyles and Krauss (1971) found, however, that $T$ and $\eta$ varied with surface roughness.

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

**Initiation of Particle Motion.** The windspeed at which sand movement starts as a result of 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 eroding particle's bouncing or ejecting off the surface bed into the airstream and moving forward is referred to as *saltation.* Almost 50–75% of the movement of soil particles is through saltation (Chepil, 1945*a*). In saltation the particles rise almost vertically, rotating from 20–1000 revolutions per second, they travel 10 times their height of rise, then return to the surface with an angle of descent of about 6–12° from the horizontal (Chepil and Woodruff, 1963; Vanoni, 1975; Zingg, 1953*b*). On striking the surface, they either rebound and continue their movement in saltation or impart most of their energy by striking other grains, causing those grains to rise upward or roll along the surface. Most of the saltating particles range from 0.1–0.5 mm in diameter.

**Creep.** The rolling or sliding of 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 the windspeed is increased, the distance moved increases and more grains are set in 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. Impact of particles in saltation usually starts movement of these fine particles. Although most soil is moved by saltation and surface creep, that moved by suspension is the most spectacular and easily recognized from a distance (Figure 1).

**Sorting.** An eroding wind has been said to act on the soil like a fanning mill acts on grain, removing the fine, porous particles and leaving the coarser and denser behind (Chepil, 1957*a;* Daniel, 1936; Moss, 1935). Of that being removed, the coarsest particles usually end up in a soil drift, and the rest enter suspension to be transported oftentimes great distances before being deposited (Malina, 1941). Chepil (1957*a*) observed that the most distinct feature in the sorting process is the peak (predominant) diameter of saltating grains. Fractions larger than the peak diameter tend to remain in the wind-eroded fields; particles smaller than that diameter tend to be carried, in suspension, far through the atmosphere.

Peak diameter of drifted material derived from sand and loamy sand fields 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 sand and loamy sand fields were composed of principally discrete, nonporous grains having an average bulk density of 2.37 g/cm$^3$. But the materials drifted from the finer textured soils were predominantly aggregates with a distinct degree of porosity and an average bulk density of 1.70 g/cm$^3$ (Chepil, 1957*a*). By applying equation 5 for peak diameters and average bulk densities, one finds that critical mean drag is about the same for both conditions: 1.7 for the single grain and 1.8 dyn/cm$^2$ for porous grains.

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

### Wind-erosion equation

Studies to understand the mechanics of the wind-erosion process, identify major factors influencing wind erosion, and develop wind-erosion control methods led to the development of a wind-wrosion equation (Chepil and Woodruff, 1963; Woodruff and Siddoway, 1965). The general functional relationship between the independent variable $E$ (the potential average annual soil loss in tons per acre), and the equivalent variables is: $E = f(I', K', C', L', V)$, where $I'$ is a soil-erodibility index; $K'$ is a soil-ridge roughness factor; $C'$ is a climatic factor; $L'$ is field length along the prevailing wind-erosion direction; and $V$ is equivalent quantity of vegetative cover.

**Erodibility Index.** Soil erodibility (ease of detachment and transport by wind) was recognized early as a primary variable affecting wind erosion. From wind-tunnel tests, Chepil (1950) determined relative erodibilities of soils reasonably free from organic residues as a function of apparent specific gravity and of proportions of dry soil aggregates in various sizes. Clods larger than 0.84 mm in diameter were nonerodible. Since then, the nonerodible soil fraction greater than 0.84 mm, as determined by dry sieving, has been used to indicate erodibility of soil by wind. In an early version of the wind-erosion equation (Chepil and Woodruff, 1954), it was one of the three major factors developed from results obtained principally with a portable wind tunnel (Zingg, 1951*a, b;* Zingg and Woodruff, 1951). During the severe wind-erosion season, January 1 through April 1, 1954, 1955, and 1956, Chepil (1960) studied 69 fields in western Kansas and eastern Colorado to determine the quantity of soil loss (tons per acre per year) for any field erodibility as determined from various field conditions. Seasonal loss was converted to annual soil loss, and relative field erodibility for each field was determined (Chepil, 1959*a;* Chepil and Woodruff, 1954).

**Ridge Roughness Factor.** Chepil and Milne (1941*a*), investigating the influence of surface roughness on intensity of drifting dune materials and cultivated soils, found that the initial intensity of drifting was always much less over a ridged than over a smooth 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.

Early versions of the wind-erosion equation (Chepil and Woodruff, 1954; Chepil and Woodruff, 1959; Chepil, Woodruff, and Zingg, 1955) contained a ridge roughness equivalent derived as the product of residue and ridge roughness. As the wind-erosion equation evolved, the influences of soil ridge roughness and vegetative cover were evaluated independently. Armbrust, Chepil, and Siddoway (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 relative quantity of eroded material and ridge roughness equivalent.

**Climatic Factor.** To determine average annual soil loss for climatic conditions other than those prevailing when the relationship between wind tunnel and field erodibility was obtained, Chepil, Siddoway, and Armbrust (1962) proposed a climatic factor. It is an index of average rate of soil movement by wind as influenced by moisture content in surface soil particles and average windspeed. The soil moisture term of the climatic factor of the wind-erosion equation was developed on the basis that erodibility of a soil varies inversely with the equivalent moisture in surface soil particles (Chepil, 1956). The windspeed term of the climatic factor is based on the rate of soil movement being proportional to windspeed cubed. Several researchers (Bagnold, 1943; Chepil, 1945*a;* Zingg, 1953*a*) have reported that when windspeed exceeds those speeds required barely to move the soil, the soil-movement rate is directly proportional to friction velocity cubed. Over a specified surface, windspeed and friction velocity are proportional.

**Field Width.** Chepil and Milne (1941*b*) reported that rate of soil movement began with zero on the windward side (side from which the wind blows) 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 wind. He called the increase in rate of soil 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, 1957*c*). Relationships between field erodibility and field width (Chepil, 1946, 1957*c;* Chepil and Milne, 1941*b*), considering the many associated factors, gave rise to the field-length term of the wind-erosion equation (Chepil and Woodruff, 1963; Woodruff and Siddoway, 1965). Field width was initially considered as the distance across a field in the prevailing wind-erosion direction. However, sometimes there is essentially no prevailing wind-erosion direction. Therefore preponderance of wind-erosion forces in the prevailing wind-erosion direction is now used to assess equivalent field width (Skidmore, 1965; Skidmore and Woodruff, 1968).

**Vegetative Factor.** Value of crop residue for controlling wind erosion was recognized early, and quantitative relationships were reported (Chepil, 1944). Amounts of wheat straw needed to protect most erodible dune sand and less erodible soils against strong winds were established (Chepil et al, 1960; Chepil et al, 1963). Standing stubble was much more effective than flattened stubble (Chepil, Woodruff, and Zingg, 1955). Standing sorghum stubble with rows perpendicular to wind direction controlled wind erosion much more effectively than did rows parallel to wind direction (Englehorn, Zingg, and Woodruff, 1952; Skidmore, Nossaman, and Woodruff, 1966).

Siddoway, Chepil and Armbrust (1965) quantified the specific properties of vegetative covers influencing soil erodibility and developed regression equations relating soil loss by wind to selected amounts, kinds, and orientation of vegetative covers, wind velocity, and soil cloddiness. Those studies led to the relationship developed 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), then relating soil loss to equivalent vegetative cover.

Craig and Turelle (1964) presented equivalent vegetative cover for additional crops, including a figure for converting quantity of various crop residues (peanuts, soybeans, shredded cotton, quar, sesame, standing cotton stalks) to quantity of equivalent flat, small-grain residue. Woodruff et al (1974) developed an equation for converting quantity of cattle feedlot manure to flat, small grain residue, wind-erosion-control equivalent. Recent research (Lyles, Schrandt, and Schmeidler, 1974) indicates that if residue is standing and is equidistantly spaced, much less residue is needed to control wind erosion than has been previously reported.

**Application.** Relations among variables are complex, and a single equation that expresses *E* as a function of the dependent variables has not been devised. The equation was solved in a stepwise procedure involving graphical solutions.

Because many tables and figures are required to solve the functional relationships of the equation, a computer solution has been developed to simplify the procedure (Fisher and Skidmore, 1970; Skidmore, Fisher, and Woodruff, 1970). Other efforts to implement the use and to improve the accuracy of the wind-erosion equation include: evaluating monthly climatic factor (Skidmore and Woodruff, 1968; Woodruff and Armbrust, 1968); assessing wind-erosion forces, prevailing wind-erosion direction (Skidmore, 1965; Skidmore and Woodruff, 1968); evaluating the erodibility of organic soils (Woodruff and Dickerson, *Wind Erosion Research Laboratory Annual Reports,* 1971 and 1972); correlating feedlot solids with other types of vegetative cover (Woodruff et al, 1974); and improving trap-strip design (Hagen, Skidmore, and Dickerson, 1972).

The equation was designed as a tool to determine the potential erosion from a particular field and the field conditions (soil cloddiness, roughness, vegetative cover, sheltering by barriers, or width and orientation of field) necessary to reduce potential erosion to a tolerable amount (Woodruff and Siddoway, 1965). The information needed to assess potential soil loss from a field is: (1) percentage of soil aggregates exceeding 0.84 mm; (2) windward knoll slope; (3) ridge height and spacing; (4) climatic factor; (5) angle of deviation of prevailing wind-erosion direction from right angles to field strip; (6) preponderance of wind-erosion forces in prevailing wind-erosion direction; (7) height of wind barrier, if any; (8) field width; (9) quantity of vegetative cover; and (10) type of vegetative cover. Information for items 4 and 6 and for determining item 5 can be obtained from the literature (Skidmore and Woodruff, 1968) by month for many U.S. locations. The percentage of soil aggregates exceeding 0.84 mm (item 1) can best be obtained by dry sieving; however, in practice, the percentage is often determined from wind-erodibility groups (Hayes, 1972), based on soil type or predominant soil textural class. Other factors can be measured in the field or estimated by comparing field conditions with similar field conditions for which the factors have been measured.

The solution of the wind-erosion equation gives the amount of erosion expected, in tons per acre per year, from a given agricultural field. The second application of the equation is to specify the amount of erosion that can be tolerated, substitute it for *E,* and then solve the equation to determine conditions—such as amount of residue and field width—needed to limit soil loss to the tolerance level. The equation has been used widely for both purposes (Hayes, 1975; Skidmore, Fisher, and Woodruff, 1970; Skidmore and Woodruff, 1968; Woodruff and Siddoway, 1965). The U.S. Soil Conservation Service has used the equation extensively to plan wind-erosion-control practices and to determine crop tolerance to wind erosion (Hayes, 1965, 1966, 1972, 1975). The equation is also a useful guide to wind-erosion-control principles (Carreker, 1966; Moldenhauer and Duncan, 1969; Woodruff et al 1972). Other uses of the equation include: (1) determining spacing for barriers in narrow strip-barrier systems (Hagen, Skidmore, and Dickerson, 1972); (2) estimating fugitive dust emissions from agricultural and subdivision lands (PEDCO-Environmental Specialists, Inc., 1973; Wilson, 1975); (3) predicting horizontal soil fluxes to compare with vertical aerosol fluxes (Gillette, Blifford, and Fenster, 1972); (4) estimating effects of wind erosion on productivity (Lyles, 1974, 1975); and (5) evaluating stubble requirements in field strips to trap windblown soil (Lyles, Schmeidler, and Woodruff, 1973.)

The principles of wind-erosion control that have evolved through the development of a wind-erosion predictive model are: pro-

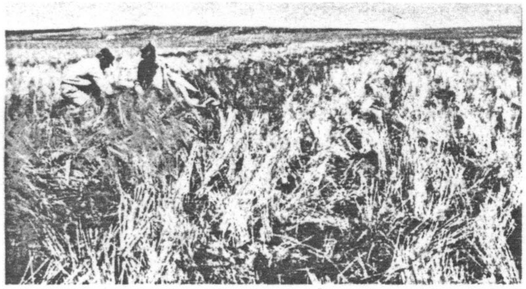

FIGURE 3. Establishing and maintaining vegatative cover is the "cardinal rule" of wind-erosion control.

duce greater percentage of clods greater than 0.84 mm, roughen the surface, reduce field length, and establish and maintain vegetative cover. This last item has been called the "cardinal rule" of wind-erosion control (Figure 3).

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Cross-references: *Conservation; Management of Soils; Wind Erosion. Vol. III: Deflation; Eolian Transport; Erosion; Wind Action. Vol. IVA: Soil Erosion. Vol. XVI: Erosion Hazards.*