Chapter 9

Soil Erosion and Conservation

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Soil erosion is a worldwide problem. Approximately 90 percent of cropland in the United States is currently losing soil above the sustainable rate. Soil erosion rates in Asia, Africa, and South America are estimated to be twice as high as those in the United States. The Food and Agriculture Organization (FAO) estimates that 140 million ha of high quality soil, mostly in Africa and Asia, will be degraded by 2010 unless better land management practices are adopted (U.S. Global Change Research Information Office, 2001).

Agricultural producers, as well as managers of nonagricultural lands, need to know what to expect in terms of soil erosion by wind and water resulting from alternative management practices. Real-world experiments are too laborious and expensive for erosion assessments and evaluation of alternative management scenarios, so computer models have been developed for this purpose. In this chapter we will focus on basic erosion processes, modeling of these processes, model applications, and erosion control. Wind erosion will be discussed first, followed by water erosion.

EROSION OF SOIL BY WIND

Erosion of soil by wind is a particularly serious problem in many arid and semiarid regions (Figure 9.1). Arid lands comprise about one-third of the world's total land area and are the home of one-sixth of the world's population (Dregne, 1976; Gore, 1979). Areas under agricultural production that are most susceptible to wind erosion include much of North Africa and the Near East, parts of southern and eastern Asia, the Siberian plains, Australia, southern South America, and the semiarid and arid portions of North America (Food and Agriculture Organization, United Nations, 1960).

Extensive soil erosion in the U.S. Great Plains during the last half of the nineteenth century and in the prairie region of western Canada during the

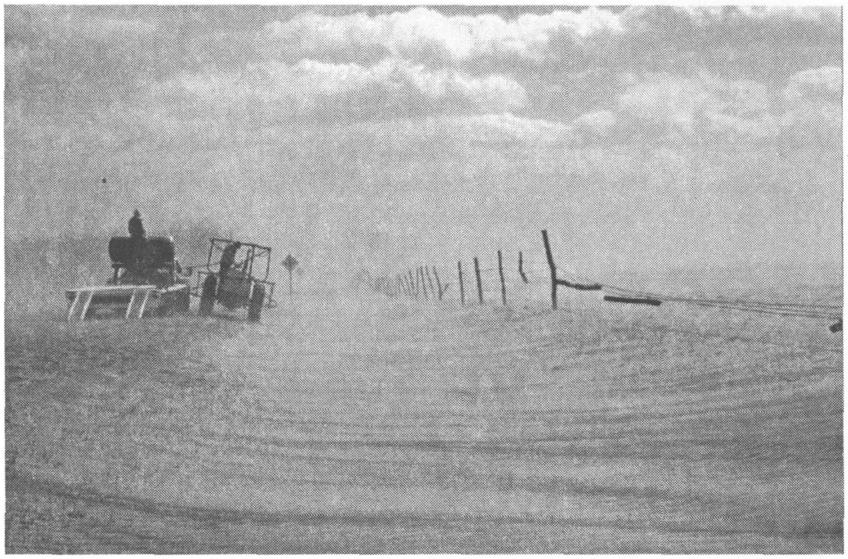

FIGURE 9.1. Severe wind erosion after wildfire in Meade County, Kansas (photograph by Edward Skidmore).

1920s warned of impending disaster. In the 1930s, a prolonged drought culminated in dust storms and soil destruction of disastrous proportions in the prairie regions of both western Canada and the Great Plains (Anderson, 1975; Hurt, 1981; Johnson, 1947; Malin, 1946; Svobida, 1940). More recently, in northern China, drought and overgrazing have caused land degradation with wind erosion resembling the dust bowl days of the 1930s in the United States (Armstrong, 2001). The Sahelian region of West Africa has seen dramatic changes over the past few decades, with decreasing rainfall, vegetation, and wildlife, and increasing wind erosion on the southern fringes of the Sahara desert.

Agricultural lands are adversely impacted by soil tillage that leaves little residue on the soil surface and by cropping systems that leave the soil surface bare for long periods of time, making it more vulnerable to wind erosion. On pastoral rangeland, the composition of pastures subjected to excessive grazing during dry periods deteriorates, the proportion of edible perennial plants decreases, and the proportion of annuals increases. The thinning and death of vegetation during droughts increase the extent of bare ground and surface soil conditions deteriorate, increasing the fraction of erodible aggregates on the soil surface. In rain-fed farming areas, removal of the original vegetation and fallow expose the soil to accelerated erosion.

Erosivity and Erodibility

For erosion to occur, there has to be a force to move the soil. Shearing stress caused by wind is this force in wind erosion and its ability to erode is called erosivity. The extent of erosion also depends on the susceptibility of the soil to erosion, which is called erodibility. As a measure of erosive wind energy Skidmore (1998) defines wind power density as

$$WPD = \rho \left(u_i^2 - u_t^2\right)^{3/2} \tag{9.1}$$

where WPD is wind power density (W m^{-2}), ρ is air density (kg m^{-3}), u_t is threshold wind speed (m s^{-1}), and u_i is measured wind speed (m s^{-1}).

Scientists recognized early that soil erodibility, the susceptibility or ease of detachment and transport by wind, was 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 proportions of dry soil aggregates of various sizes. Clods larger than 0.84 mm in diameter were immobile in the range of wind speeds used in the tests. In addition to aggregate size distribution, soil erodibility depends on aggregate stability, soil surface wetness, crusting, and amount of loose material on a crust.

Basic Processes

Wind erosion consists of entrainment of loose and abraded particles, followed by their transport and deposition.

Entrainment

The way the first particles are moved has received less attention than the modes of transport. Before 1962, most researchers were satisfied by Bagnold's (1941) description of particles rolling along the surface by direct wind pressure for about 30 cm before starting to bounce off the ground. Bisal and Nielsen (1962) concluded, after observing particles in a shallow pan mounted on the viewing stage of a binocular microscope, that most erodible particles vibrated with increasing intensity as wind speed increased and then left the surface instantly as if ejected.

More recently, particle entrainment has been studied and described in considerable detail (Anderson, Sørensen, and Willetts, 1991; Rasmussen and Rasmussen, 1998). On many agricultural soils, immobile aggregates and crusts are first abraded by incoming sediment before being entrained (Hagen, 1991b; Rice and McEwan, 2001).

Transport

Transport can occur in three modes: surface creep, saltation, and suspension (Figure 9.2). Sand-sized soil particles or aggregates 500-1000 μm in diameter, too large to leave the surface in ordinary erosive winds, are pushed, rolled, and driven by the impacts of spinning particles in saltation. In high winds, the whole surface appears to be creeping slowly forward. The rippling of wind-blown sand has been attributed to unevenness in surface creep flow (Bagnold, 1941). Creep appears nearly passive in the erosion process, but creep-sized aggregates may abrade into the size range of saltation and suspension and, thus, shift modes of transport. Creep aggregates seldom move far from their points of origin (Lyles, 1988).

In saltation, individual particles lift off the surface and follow distinctive trajectories under the influence of air resistance and gravity. Such particles (100-500 μm) rise at fairly steep angles but are too large to be suspended by the flow. They return to the surface where they may abrade themselves or other aggregates on impact, or they may rebound or embed themselves and initiate movement of other particles. Most saltating particles rise no higher than 30 cm (Lyles, 1988).

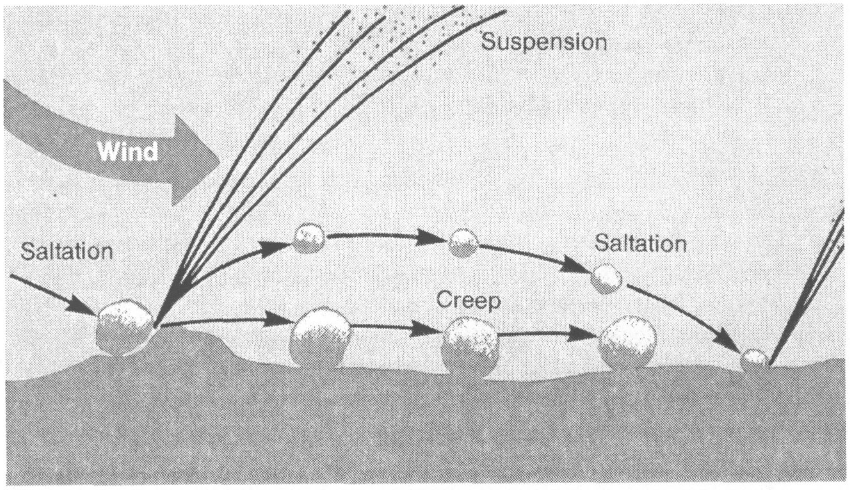

FIGURE 9.2. Airborne sediment transport by means of surface creep, saltation, and suspension (*Source:* USDA, Soil Conservation Service, 1989.)

Suspension refers to the transport of very small soil particles that are generally removed from the local source area. They may be deposited on the neighbor's farm or several states downwind. Suspended particles can range in size from about 2 to 100 μm, with mass median diameter of approximately 50 μm in an eroding field (Chepil, 1957; Gillette and Walker, 1977). Some suspension-sized particles are present in the soil, but most are created by abrasive breakdown during erosion. 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 (Lyles, 1988).

The relative amount of sediment in various transport modes varies with downwind distance and field surface. The percentage of sediment in suspension generally becomes greater further downwind. Obviously, there will be a greater percentage in suspension when the source material from the surface is finer.

Deposition

Suspended particles start to settle when wind speed and turbulence slow down. They also move to the surface of the earth by diffusion. Larger and heavier particles settle first. In long-distance transport, particles <20 μm in diameter predominate because the larger particles have significant sedimentation velocities (Gillette, 1977). Suspended material may also be deposited with rainfall. For saltation and creep, deposition occurs when sediment mass flux exceeds transport capacity of the wind for a given surface condition. Standing biomass and soil ridges intercept particles transported in saltation and creep mode. Saltating particles usually are deposited in a fence row, ditch, trap strip, wind break, or on the edge of a vegetated area downwind (Lyles, 1988).

MODELING WIND EROSION

Models can be useful tools to assess erosion and evaluate the effect of alternative management scenarios on erosion. The wind erosion equation (WEQ) proposed by Chepil and Woodruff (1963) and Woodruff and Siddoway (1965) developed as a result of investigations into the mechanics of the wind erosion process, the major factors influencing wind erosion, and the development of wind erosion control methods. The equation expressed in function form is:

$$E = f(I, K, C, L, V) \qquad (9.2)$$

where E is the potential average annual soil loss, I is the soil erodibility index, K is the soil ridge roughness factor, C is the climate factor, L is unsheltered distance across a field, and V is the equivalent vegetative cover.

Solving the functional relationships of the wind erosion equation as presented by Woodruff and Siddoway (1965) required the use of tables and figures. The awkwardness of the manual solution prompted a computer solution (Fisher and Skidmore, 1970; Skidmore, Fisher, and Woodruff, 1970a, b) and development of a slide rule calculator (Skidmore, 1983). After the arrival of personal desktop computers, the model was adapted for use with them (Halsey et al., 1983) and interactive programs (Erickson et al., 1984). Cole, Lyles, and Hagen (1983) adapted the Woodruff and Siddoway (1965) model for simulating daily soil loss by wind erosion as a submodel in EPIC (Williams, Jones, and Dyke, 1984). The latter version was simplified by fitting equations (Skidmore and Williams, 1991) to the figures of Woodruff and Siddoway (1965).

Some limitations in WEQ were recognized (Skidmore, 1976) and various improvements have been incorporated. These include computing erosion by periods (Bondy, Lyles, and Hayes, 1980; Fryrear, 1981; Lyles, 1983; Sporcic and Nelson, 1999); accounting for preponderance, field shape and orientation, and row direction (Skidmore, 1965, 1987; Skidmore, Nossaman, and Woodruff, 1966); improved formulation of the climatic factor and extended climate database (Skidmore and Woodruff, 1968; Skidmore, 1986; Skidmore, Tatarko, and Wagner, 1994); and estimation of small grain equivalents expanded to additional plants and conditions (Lyles and Allison, 1980, 1981; Armbrust and Lyles, 1985; Skidmore and Nelson, 1992).

Despite the many improvements to WEQ, complex interactions between variables are not accounted for in calculation procedures and it is not easily adapted to untested conditions or climates far different from those of the central Great Plains where it was developed. Therefore, the United States Department of Agriculture-Agricultural Research Service (USDA-ARS) appointed a team of scientists to take a leading role in developing the new Wind Erosion Prediction System (WEPS) as a replacement for the "mature" WEQ (Hagen, 1991a; Wagner, 1996; USDA, 1995). Advances in erosion science and the increased power of personal computers have allowed the adoption of more flexible, processed-based erosion prediction technology.

WEPS is a daily time-step computer model that predicts soil erosion via simulation of the physical processes controlling wind erosion. It is intended primarily for soil conservation and environmental planning. WEPS 1.0 is the first implementation of WEPS intended for use by the USDA-Natural Resources Conservation Service (NRCS). It includes a graphical user interface to allow the user to easily select climate stations, specify field dimensions, pick a predominant soil type, and describe wind barriers and management practices applied to an agricultural field. This interface allows the user to quickly assess a site's susceptibility to wind erosion and evaluate the impacts that alternative practices and conditions might have on reducing that susceptibility (Wagner and Tatarko, 2001).

WEPS is modular in design and consists of a main supervisory routine and several submodel components (USDA, 1995). The main routine handles the time steps in the model, reads the input files, controls the individual submodel routines, and generates the output reports. Each of the individual submodel components likewise performs specific duties within the WEPS model.

The erosion submodel decides if erosion can occur based on the current surface roughness, quantity of flat and standing biomass, aggregate size distribution, crust and rock cover, loose erodible material on a crust, and soil wetness. If the surface conditions are susceptible and wind speed is sufficient, erosion and deposition are simulated on a subhourly basis (Hagen, Wagner, and Skidmore, 1999). During erosion, the submodel individually simulates the saltation/creep and suspension components of wind-eroded soil. This approach was used because the saltation/creep component has a defined transport capacity, whereas the suspension component generally continues to increase over the entire length of eroding fields. Individual processes simulated include entrainment of loose material and abrasion of clods and crusts.

The hydrology submodel estimates soil surface wetness, accounts for changes in soil temperature, and maintains a soil-water balance based on daily amounts of snow melt, runoff, infiltration, deep percolation, soil evaporation, and plant transpiration. The soil submodel tracks changes in soil and surface temporal properties in response to various weather processes such as wetting/drying, freezing/drying, freezing/thawing, precipitation amount, and time. The crop submodel simulates the growth of crop plants. It can simulate a variety of crops and plant communities while accounting for water and temperature stresses. It calculates daily biomass production of roots, leaves, stems, and reproductive organs as well as leaf and stem areas.

The decomposition submodel simulates the decrease in crop residue biomass from microbial activity. The decomposition process is modeled as a first order reaction, with temperature and moisture as the driving variables. It maintains separate decomposition pools for residue type (parent material), plant component (stems and roots), location (standing, flat, buried), and residue age. The management submodel simulates the various cultural practices applied to an agricultural field. These include primary and secondary tillage, cultivating, planting/seeding, harvesting, irrigating, and burning and grazing operations. Each individual operation is described as a series of processes that reflect the physical changes in the soil, surface, crop, and residue status.

The modular design of WEPS is intended to allow for easy updating and revising of the science model, or even replacing specific components and/or sections in the future as knowledge and understanding of erosion, climate, plant growth, and other processes improve (Wagner and Tatarko, 2001). Because WEPS did not progress as rapidly as envisioned, it was decided to quick-fix some of the more serious problems associated with WEQ. Hence, a Revised Wind Erosion Equation (RWEQ) (Fryrear et al., 1998; Zobeck et al., 2001) was born. RWEQ is a factor multiplication model with factors similar to those used in WEQ.

Other models emerging on the wind erosion prediction scene include TEAM (Gregory and Darwish, 2001), WEAM (Shao, Raupach, and Leys, 1996), an adaptation of EPIC (Skidmore and Williams, 1991), and models by Berkofsky and McEwan (1994), and Rice et al. (1999).

The Texas Tech Erosion Assessment Methodology (TEAM) model is a mathematical model that simulates the detachment and maximum transport rate of soil and predicts the concentration (loading) of dust into the environment based on a single storm event, modeling the interaction of wind, soil, resistance, and soil roughness factors (Gregory and Darwish, 2001). TEAM also models saltation concentration, particle size distribution, and provides visibility predictions. It has been used primarily to evaluate real-world field and climatic conditions (primarily dust storm prediction and air quality safety analysis).

The overall focus of WEAM (Wind Erosion Assessment Model) is to estimate sand drift and dust entrainment (aerial suspension) of dry, bare soil subject to a given wind condition. The model considers creep, saltation, and suspension, and specifically the mobilization of soil particles due to wind forces (Shao, Raupach, and Leys, 1996). The model is based on empirical equations, is not computer-based, and is primarily a synthesis of recent studies in the wind erosion field involving the physical processes governing sand drift and dust entrainment. The model only predicts wind erosion for a given, static condition; evolution of surface properties due to natural weathering, cultivation/grazing, or abrasion from wind erosion is not provided.

The Erosion Productivity Impact Calculator (EPIC) (Williams, Dyke, and Jones, 1983; Williams, Jones, and Dyke, 1984, 1993) was developed to assess soil erosion and soil productivity. It is a continuous simulation model that is generally used to predict changes in soil productivity and water quality over large temporal domains. The major components in EPIC are weather simulation, hydrology, erosion/sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control. Cole, Lyles, and Hagen (1983) adapted WEQ for simulating daily wind erosion as a submodel in EPIC and later modified it (Skidmore and Williams, 1991). Some recent developments have focused on problems involving water quality and global climate change. Additions to EPIC include the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) (Leonard, Knisel, and Still, 1987) pesticide fate component, and nitrification and volatilization submodels. These and other developments extend EPIC's capability to deal with a wide variety of agricultural management problems. With these changes it has been renamed as the Environmental Policy Integrated Climate model (Williams et al., 1996).

Berkofsky and McEwan (1994) proposed a partial differential equation for the prediction of rate of change of dust concentration in a thin layer near the ground. Detachment, transport, and deposition were included in the equation. The planetary boundary layer was divided into a surface layer, a transition layer, and an inversion layer. Rice et al. (1999) described a conceptual model for the prediction of wind erosion rates dependent on the distribution of impact energy delivered to the surface by saltating grains, and the distribution of local surface strength.

Model Applications

Scientists and practitioners have used WEQ with various modifications for the past 35 years. NRCS field workers have used the equation extensively to plan wind erosion control practices (Hayes, 1966), classify erodibility of soils (Woodruff and Siddoway, 1965; USDA, 1988), and determine highly erodible land for all farms in the United States in association with the Food Security Act of 1985 (Federal Register, 1992). Hayes (1965) also used WEQ to estimate crop tolerance to wind erosion. The equation is a useful guide to wind erosion control principles as well (Carreker, 1966; Moldenhauer and Duncan, 1969; Woodruff et al., 1972).

Other uses of the equation include: (a) determining spacing for barriers in narrow strip-barrier systems (Hagen, Skidmore, and Dickerson, 1972); (b) estimating fugitive dust emissions from agricultural and subdivision lands (PEDCO-Environmental Specialists, Inc., 1973; Wilson, 1975); (c) predicting horizontal soil fluxes to compare with vertical aerosol fluxes (Gillette, Blifford, and Fenster, 1972); (d) estimating the effects of wind erosion on soil productivity (Lyles, 1974; Williams, Jones, and Dyke, 1984); (e) delineating those croplands in the Great Plains where various amounts of crop residues may be removed without exposing the soil to excessive wind erosion (Skidmore, Kumar, and Larson, 1979); and (f) estimating erosion hazards in a national inventory (USDA, Soil Conservation Service, 1984).

WEPS is intended to be the "tool of choice" for planning soil conservation systems, providing environmental planning and assessment evaluations, and estimating off-site impacts of wind erosion (Wagner, 1996). The NRCS is implementing WEPS 1.0 for use as a conservation and planning tool on agricultural croplands in preparation for the expected 2002 U.S. Farm Bill. However, there are limitations in this initial version that preclude full applicability to a wider range of lands susceptible to wind erosion. Thus, to fulfill additional wind erosion prediction requirements, WEPS needs to be enhanced and extended. Based upon customer and user input, the following needs have been identified: (a) extend WEPS to nonhomogeneous soils and variable topography; (b) incorporate a multispecies plant growth model component into WEPS; (c) incorporate both water (Water Erosion Prediction Project [WEPP]) and wind (WEPS) erosion simulations into a single science model; (d) extend WEPS technology to handle needs for management of range and disturbed lands including military training lands; and (e) extend WEPS technology to handle organic soils.

Lopez (1998) estimated the potential dust flux within an agricultural field in Central Aragon, Spain, using a dust emission model developed by Maticorena and Bergametti (1995). This model is based on the threshold wind shear velocity being a function of aggregate size distribution and roughness length of the soil surface. The observed reduction in soil erodibility with time was probably due to a limited supply of erodible particles at the soil surface. This study underlines the need to consider the temporal variability of the surface conditions in wind erosion research and models.

Lyons et al. (1998) described a system comprised of a physically based wind erosion model driven by data from a high resolution atmospheric model and land surface data from detailed geographical information system (GIS) databases. The model considers the capacity of the wind to entrain and transport particles and the ability of the surface to resist wind erosion through consideration of the effects particle size, frontal area index, topsoil moisture, and surface crusting. The system was applied to an investigation of wind erosion in Australia. It was found to be effective in predicting the timing and location of wind erosion events.

Erosion Control

In general, to control erosion, the capacity of the erosive agent (erosivity) and/or the susceptibility of the surface material (erodibility) must be reduced. Principles for controlling wind erosion include establishing and maintaining sufficient vegetative cover; producing a rough, cloddy surface;

reducing surface wind speed and effective field width with barriers; and stabilizing soil with various materials (Woodruff et al., 1972).

Vegetation—Crops and Crop Residues

Living vegetation or residue from harvested crops protects the soil against wind erosion (Figure 9.3). 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 do rows parallel to wind direction (Englehorn, Zingg, and Woodruff, 1952; Skidmore, Nossaman, and Woodruff, 1966). Flattened stubble, though not as effective as standing, also protects the soil from wind erosion (Chepil, Woodruff, and Zingg, 1955).

Soon after the disastrous "dirty thirties" in the U.S. Great Plains, stubble-mulch systems were demonstrated to be feasible for reducing wind erosion on cultivated land (Duley, 1959). Stubble mulching is a crop residue management system using tillage, generally without soil inversion and usually

FIGURE 9.3. Maintaining crop residue on the surface protects soil from the wind (photograph by Edward Skidmore).

with blades or V-shaped sweeps (McCalla and Army, 1961; Mannering and Fenster, 1983). The goal is to leave a desirable quantity of plant residue on the surface of the soil at all times. Residue is needed for a period of time even after a new crop is planted to protect the soil from erosion and to improve infiltration. The residue used is generally that remaining from a previous crop. Direct seeding into residue and nontillaged areas leaves even more residue on the surface than stubble mulching and, consequently, protects the soil even better against wind erosion.

Early studies quantified specific properties of vegetative covers influencing wind erosion (Chepil, 1944; Chepil, Woodruff, and Zingg, 1955; Siddoway, Chepil, and Armbrust, 1965). These studies 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). Research efforts have continued to evaluate the protective role of additional crops (Craig and Threlle, 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 (Lyles, Schmeidler, and Woodruff, 1973; Skidmore and Siddoway, 1978; Skidmore, Kumar, and Larson, 1979). Using residue for reducing wind erosion is probably the most effective and practical method in many situations, especially with the move toward less tillage that is going on in many parts of the world (Peterson, Westfall, and Cole, 1993; Peterson et al., 1996; Farahani et al., 1998; Anderson et al., 1999).

Tillage

Chepil and Milne (1941), while investigating the influence of surface roughness on drifting dune materials and cultivated soils, found that the initial intensity of drifting was always much less over a ridged than 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 sediment flow varied inversely with surface roughness.

When ridges are mostly gone, vegetative cover is depleted, and the threat of wind erosion continues, a rough, cloddy surface that is resistant to the force of wind can be created on many cohesive soils with appropriate "emergency tillage." Lyles and Tatarko (1982) found that chiseling of growing winter wheat on a silty clay soil greatly increased nonerodible surface aggregates without affecting grain yield. Listers, chisels, cultivators, oneway disks 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. Because clods eventually disintegrate (sometimes rapidly), emergency tillage offers, at best, only temporary wind-erosion control (Woodruff, Chepil, and Lynch, 1957; Woodruff et al., 1972).

Barriers

Use of wind barriers is an effective method of reducing field width. Barriers have long been recognized for their value in controlling wind erosion (Bates, 1911). Hagen (1976) and Skidmore and Hagen (1977) developed a model that, when used with local wind data, shows wind barrier effectiveness in reducing wind erosion forces. Barriers will reduce wind forces more than they will wind speed (surface wind shear stress is proportional to wind speed squared). A properly oriented barrier, 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 in force will be 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. They include annual crops, such as small grains, corn, sorghum, Sudan grass, and sunflower (Carreker, 1966; Fryrear, 1963, 1969; Hagen, Skidmore, and Dickerson, 1972; Hoag and Geiszler, 1971), and tall wheatgrass (Aase, Siddoway, and Black, 1976; Black and Siddoway, 1971).

Most barrier systems for controlling wind erosion, however, occupy space that could otherwise be used to produce crops. Perennial barriers grow slowly and are often difficult to establish (Dickerson, Woodruff, and Banbury, 1976; Woodruff et al., 1976). Such barriers also compete with crops for water and plant nutrients (Lyles, Tatarko, and Dickerson, 1983). Thus the net effect for many tree-barrier systems is that their use may not benefit crop production (Frank, Harris, and Willis, 1977; McMartin, Frank, and Heints, 1974; Skidmore, Hagen, and Teare, 1975; Skidmore et al., 1974; Staple and Lehane, 1955). Perhaps the tree-barrier systems could be designed so that the barrier becomes a useful crop, furnishing nuts, fruits, or wood.

Stabilizers

Various soil stabilizers have been evaluated in the search for 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, Schrandt, and Schmeidler, 1974). Several tested products successfully controlled wind erosion for a short time but many were more expensive than equally effective wheat straw anchored with a rolling disk packer (Chepil et al., 1963). The following are criteria for surface-soil stabilizers (Armbrust and Lyles, 1975):

1. 100 percent of the soil must be covered.
2. The stabilizer must not adversely affect plant growth or emergence.
3. Erosion must be prevented initially and reduced for the duration of the severe erosion hazard, usually for at least two months each season.
4. The stabilizer should apply easily and without special equipment.
5. Cost must be low enough for profitable use.

Armbrust and Lyles (1975) found five polymers and one resin-in-water emulsion that met all these requirements.

EROSION OF SOIL BY WATER

Erosion of soil by water occurs throughout the world, but especially in the more humid regions. Erosion results in the loss of topsoil that is not easily replaced. Estimates of erosion are essential to issues of land and water management, including sediment transport and storage in lowlands, reservoirs, estuaries, and irrigation and hydropower systems. Another issue is water pollution by contaminants carried with sediment into water bodies.

Erosivity and Erodibility

The potential ability of rainfall to cause erosion is referred to as its erosivity. When raindrops strike bare soil, practically all of the energy is consumed as work done against the soil surface in the disruption of soil aggregates, compaction of the soil surface, and splash of soil particles into the air (Rosewell et al., 2000). Erosivity is related to the kinetic energy of rainfall, which can be related to rainfall amount and intensity. The Universal Soil Loss Equation (USLE) (Wischmeier, 1959) includes a method for calculating storm kinetic energy E and erosivity R. The storm kinetic energy can be computed as the sum of each rain intensity group l_i as:

$$E = (210 + 89 \log l_i) D_i \tag{9.3}$$

where E is kinetic energy (J m^{-2} cm^{-1}), l_i is rainfall intensity (cm h^{-1}) and D_i is rain depth (cm) for intensity group l_i of the rainstorm. The erosivity parameter R, according to USLE, presents for a large group of soils the best linear relation between soil erosion and rainstorm erosivity:

$$R = EI_{30} \tag{9.4}$$

where R is erosivity (J m^{-2} h^{-1}), and I_{30} is the maximum rainfall intensity (cm h^{-1}) for a continuous 30-minute period of rainfall (Morin, 1996). Lal and Elliott (1994) present several ways to estimate and measure rainfall erosivity.

Soil erodibility is a measure of the soil's susceptibility to detachment and transport by the agents of erosion (Lal and Elliot, 1994). Le Bissonnais (1996) defined soil erodibility as the inherent soil property to react to water action in (1) reducing infiltration rate and decreasing soil surface roughness due to aggregate breakdown, i.e., increasing the risk of runoff, and (2) being detached and transported by the resulting runoff. The ease with which the soil matrix yields to a raindrop impact is called detachability of the soil. As the strength of the soil to withstand the erosive force of the impacting drop increases, the detachability of soil decreases (Sharma, 1996).

The response of a soil to erosion processes is complex, and is influenced by soil properties such as texture, structural stability, organic matter content, clay mineralogy, and chemical constituents. Some of these properties, such as organic matter, can be altered over time by land use, management practices, and farming systems. Erosion of the surface layers can expose less-erodible subsoils, which may have different properties than the surface. Consequently, the erodibility of a soil can change with time (Lal and Elliot, 1994). It also varies with soil moisture, temperature, and soil disturbance (Young, Romkens, and McCool, 1990).

Soil texture is important in determining erodibility. Sandy soils have lower runoff rates and are more easily detached, but less easily transported than silt soils. Clay soils are not easily detached, but lower infiltration rates may lead to greater runoff and increased erosion. Silt soils tend to have the greatest erodibilities since particles are easily detached and transported, and consolidation of subsoils, or subsoils with higher clay contents, can lead to greater runoff. The greatest erosion is often associated with high silt loess soils, as found in China's Yellow River watershed (Lal and Elliot, 1994).

Basic Processes

The predominant processes that determine erosion are infiltration, runoff, detachment and transport by raindrops and overland flow (interrill erosion), detachment and transport by concentrated flow (rill erosion), and deposition (Lal and Elliot, 1994).

The process of erosion of soil by water starts with the detachment and transport of soil particles by impact force of raindrops and drag force of overland flow. The dominance of one force over the other determines the controls on the processes of detachment and transport. Raindrop impact provides the primary force needed to initiate detachment of soil particles from the soil mass. Raindrop splash and overland flow transport sediment in a downslope direction. Sediment must be detached from the soil mass or be in a detached state before it can be transported (Sharma, 1996).

The water erosion process can be detachment limited or transport limited (Foster, 1982). The process is transport efficient or detachment limited if all particles generated in an eroding area move across the lower slope boundary. The process is transport limited if all particles detached in an upslope area are not carried across the downslope boundary. Generally, all particles that are detached are not transported out of the eroding area. The process of settling of detached and transported sediments is called deposition. Detachment, transport, and deposition of sediment are three integral processes of soil erosion (Rose, 1985).

Detachment

Soil detachment by raindrop impact is the principal erosion process controlling interrill soil erosion, even though sufficient surface flow must be available for transport of the detached particles (Bradford and Huang, 1996). The detachment capacity of interrill flow is negligible compared to that of raindrop splash (Young and Wiersma, 1973) because of the low shear stresses of the thin sheet flow.

The process of soil detachment by raindrops is best understood by studying the mechanism of soil detachment from the impact of a single drop (Ghadiri and Payne, 1977). Using high-speed photography, Mutchler (1967) and Al-Durrah and Bradford (1982) describe the mechanism of raindrop impact on the soil surface and the resulting soil detachment and sediment splash. When a raindrop impacts a saturated soil surface, a hemispheric cavity is formed on the surface. The vertical compressive stress of the drop is then transformed into lateral shear stress of radial flow of water jetting away from the center of the cavity. At this stage, soil particle detachment is caused by the shear stresses of the radial flow acting on the bottom and sides of the cavity (Sharma, 1996). The amount of soil detachment from the cavity sides will be determined by the magnitude of soil deformation that takes place in the earlier stages of cavity development and by the cohesive forces resisting the shear stresses (Al-Durrah and Bradford, 1982).

Soil detachment by concentrated runoff results in rill erosion (Bryan, 1987). It usually affects only a small proportion of the land surface, but is much more visible than interrill erosion (Rosewell et al., 2000). Rill erosion is erosion in numerous small channels, which can be obliterated by normal tillage. A depth of less than 300 mm may be used as a criterion to distinguish rills from gullies (Houghton and Charman, 1986).

Transport

Commonly known as splash erosion, air splash occurs immediately after raindrop impact initiates soil detachment. The droplets generated after impact radiate outward from the center of the impact while encapsulating solids and carrying them to the landing points. Air splashing of solids declines rapidly as the depth of water covering the soil surface increases, reaching near negligibility at depth of about 2 mm (Moss, 1988). For normal impacts on horizontal surfaces, splash produces only random particle movement. However, air splash can cause net soil transport in one direction, initially, under the influence of slope or wind and, secondly, due to preferential movement of solids from areas of high activity to those of low activity (Sharma, 1996). The apparent absence of thick, extensive deposits attributable to air splash suggests that the mechanism is seldom a major transporting agent (Moss, 1988). However, more recent studies (Erpul, 2001) show that air splash can be of importance in overland flow, especially under inclined (wind-driven) rainfall.

As soon as the process of runoff starts, the overland flow, which is inherently more unidirectional than air splash, begins to transport solids downslope. The solids transported by the flow can be split into suspended and bed loads. Depending on the slope and surface roughness, flow alone can only transport small-sized particles in suspended load. Bed load particles not transported by flow alone remain on the bed until lifted back in the flow by force of raindrops impacting the shallow overland flow (Kinnell, 1988). Sediment may be washed into rills where it may be further transported into gullies, channels, and eventually end up in water bodies.

Gullies are relatively permanent, steep-sided water courses that experience ephemeral flows during rainstorms. Compared with stable river channels which have a relatively smooth, concave-upward, long profile, gullies are characterized by a head cut and various steps or knick points along their course. Gullies have greater depth and smaller width than stable channels, carry larger sediment loads, and display very erratic behavior so that relationships between sediment discharge and runoff are frequently poor. Gullies are almost always associated with accelerated erosion (Morgan, 1995).

Deposition

Sediment settles on the surface when overland flow is obstructed due to surface roughness, plant stalks, and stubble mulches, or when flow turbulence is lowered due to decrease in slope steepness or frequency of rainfall impact (Sharma, 1996). The settling velocity of an aggregate or primary particle is a function of its size, shape, and density. The rate of deposition is related to the velocity of flow and to the concentration and density of a given sediment size (Hairsine and Rose, 1991). Deposition may facilitate the formation of a seal, because of sediment clogging pores, thus reducing infiltration and increasing runoff.

MODELING WATER EROSION

As with wind erosion, computer models have been developed for the simulation of water erosion. The Universal Soil Loss Equation (USLE) (Wischmeier, 1959; Wischmeier and Smith, 1978) predicts average annual soil loss. It is an empirical model based on a large number of experimental data from small plots. USLE was developed to examine the long-term effect of land management options on erosion of soil by water and has been widely used in many parts of the world. The equation:

$$A = RKLSCP \tag{9.5}$$

estimates the average annual soil loss (A) from factors that depend on rainfall erosivity (R), soil erodibility (K), topography (L and S), crop and crop management (C), and erosion control practice (P). Modifications of USLE have resulted in the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991; RUSLE2, Foster et al., 2001) and the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977). Morgan, Morgan, and Finney (1984) developed a model to predict annual soil loss from field-sized areas on hillslopes which, while it retains the simplicity of USLE, encompasses some of the advances in understanding of erosion processes.

The Water Erosion Prediction Project model (WEPP) (Lane and Nearing, 1989) is being developed by an interagency group of scientists in the United States. WEPP is a process-based erosion prediction model meant to replace USLE. It simulates the erosion processes of soil detachment, transport, and deposition, as well as the processes that lead to erosion, including infiltration and runoff. It also simulates plant growth, senescence, and residue decomposition. The effects of tillage processes and soil consolidation are also modeled. Erosion and deposition are calculated based on a predefined value of sediment transport capacity estimated from flow hydraulics, slope, and sediment properties. Net erosion or deposition is estimated by the difference between sediment load and transport capacity (Huang, Darboux, and Zartl, 2001).

WEPP is/will be available in three versions: (1) a hillslope version (Figure 9.4) that predicts soil erosion from a single hillslope of any length. The hillslope can have a complex shape and can include numerous soils and crops along the hillslope; (2) a watershed version that links hillslope elements together with channel and impoundment elements; and (3) a grid or GIS version is envisioned that will link numerous hillslopes to model the erosion and sediment transport processes in large basins. WEPP will model basins that can have a single storm basinwide, and where upland, rather than channel, processes dominate sediment yields.

The European Soil Erosion Model (EUROSEM) (Morgan, Quinton, and Rickson, 1993) simulates erosion, transport, and deposition of sediment over the land surface by interrill and rill processes. It is designed as an event-based model for both individual fields and small catchments. Model outputs include total runoff, total soil loss, the storm hydrograph, and the

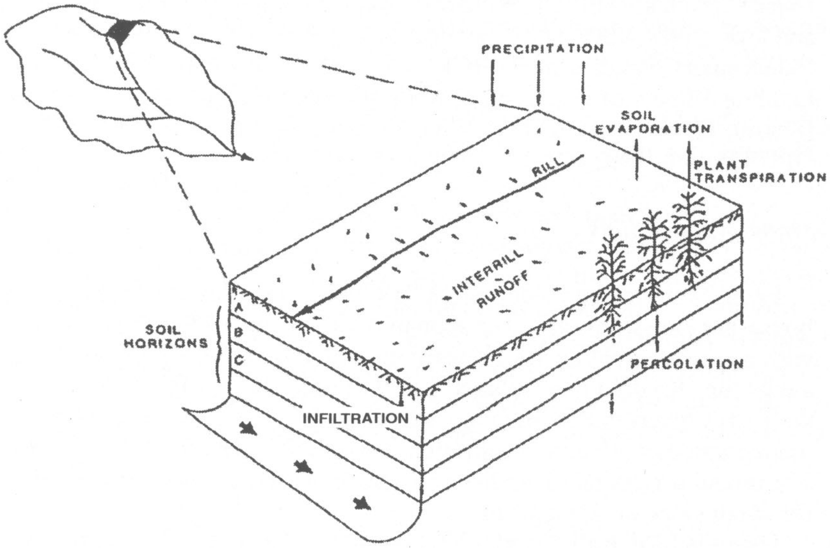

FIGURE 9.4. WEPP hillslope profile within a small watershed, showing hydrological processes (from Savabi and Williams, 1995).

storm sediment graph. EUROSEM simulates the effects of plant cover on rainfall interception, infiltration, flow velocity, and splash erosion (Morgan et al., 1998). It can be used in three different modes (Deinlein and Böhm, 2000). Erosion can be predicted for a (1) single plane or element that represents a small field with reasonably uniform slope, soil, and land cover conditions; (2) consecutive series of multiple planes or cascading elements that represent a heterogeneous slope, with each plane having uniform slope, soil, and land cover characteristics; and (3) small catchment, which is conceptualized as a cascading series of multiple planes and branching channels, with the plane elements contributing their runoff to the channels.

Additional models simulating soil erosion by water include the LImburg Soil Erosion Model (LISEM) (de Roo et al., 1998); the KINematic runoff and EROSion model (KINEROS) (Woolhiser, Smith, and Goodrich, 1990); EROSION-2D/3D (Schmidt, 1996); the Sediment Transport Model (STM-2D/3D) (Biesemans, 2000), which is a modification of EROSION-2D/3D; and the Simulation Model of Overland flow and ERosion Processes (SMODERP) (Dostál, Váška and Vrána, 2000).

Other models simulate complex processes of nutrient cycling or water pollution in addition to soil erosion by water. They include the AGricultural Non-Point Source model (AGNPS) (Young et al., 1994); the Erosion Productivity Impact Calculator (EPIC) (Williams, Dyke, and Jones, 1983; Williams, Jones, and Dyke, 1984, 1990); the Chemicals, Runoff and Erosion from Agricultural Management Systems model (CREAMS) (Knisel, 1980); the Groundwater Loading Effects of Agricultural Management Systems model (GLEAMS) (Knisel, Leonard, and Davis, 1933; Leonard, Knisel, and Still, 1987); and OPUS (Smith, 1992).

Model Applications

Favis-Mortlock and Guerra (2000) studied the influence of global greenhouse-gas emissions on soil erosion in Brazil using WEPP. They concluded, with a considerable band of uncertainty, that erosion rates may rise at the study site. Kincaid and Lehrsch (2001) tested the WEPP hillslope model with data taken under traveling lateral irrigation in southern Idaho. The main parameter affecting infiltration and runoff was hydraulic conductivity. The model was found to predict average runoff and soil loss reasonably well for small slope areas (< 40 m).

Using WEPP, Kalita et al. (2001) conducted a study to predict sediment and runoff from a watershed at the Fort Riley military training area in Kansas. Sediment and runoff data were collected with the help of a cutthroat flume and an automatic sampler installed at the watershed outlet. WEPP model input parameters were collected, measured, and estimated. Sediment and runoff data showed good agreement between measured and predicted results for individual events and excellent agreement for seasonal totals.

EUROSEM was evaluated against data for a watershed in Oklahoma. Model calibration was carried out using data for events from training periods with similar rainfall patterns and soil conditions to that of the test events. Once calibrated, the model was applied to four test events. EUROSEM simulated the total runoff and soil loss from three of these events quite well, but failed to reproduce the hydrographs and sedigraphs (Quinton and Morgan, 1998).

De Roo (2000) conducted a study on flood prevention and soil conservation in the Netherlands. He found LISEM to be a useful tool for planning cost-effective measures to mitigate the effects of runoff and erosion. Stolte et al. (2001) used LISEM to calculate water and sediment discharge in a 1,800 m^2 agricultural watershed on the Loess Plateau of China. Water content of the soil, and water and sediment discharge were measured automatically. Calibration was carried out for one event by adjusting saturated conductivity. Results showed reasonable agreement between measured and calculated water and sediment discharge.

Grunwald and Frede (2000) applied a modified version of AGNPS to three German watersheds with satisfactory results for both hydrology and sediment delivery. SMODERP was used to evaluate plans for the protection of urban areas against surface runoff and sediment from a small agricultural watershed (Dostál, Váška, and Vrána, 2000).

The EROSION-3D model has been successfully applied for estimating yields of sediment and sediment-bound heavy metals of drinking water reservoirs in the Osterzgebirge region of Saxony, Germany (Schmidt and von Werner, 2000). Model simulations showed that sediment yield can be considerably reduced if all agricultural land is managed using conservation tillage. EROSION-3D will be used for simulating erosion and sediment deposition before and after military training periods so that the impacts of training activities on sediment production can be demonstrated (Deinlein and Böhm, 2000). Erosion was simulated in support of land management in the loess belt of Flanders, Belgium, using STM-2D/3D (Biesemans, 2000), implemented in a two-dimensional hillslope and a three-dimensional watershed version.

Erosion Control

To control soil erosion by water, runoff must be eliminated or reduced to a water flow rate that cannot transport detached soil particles. Because water lost as runoff is of no benefit for crop production, controlling runoff is also essential for water conservation purposes. Conservation and minimum tillage, mulches, and cover crops prevent runoff initiation by intercepting raindrops. High infiltration rates are maintained and, therefore, runoff and erosion are minimized. Practices that retain runoff on cropland include contour tillage, furrow dikes, level terraces, and land leveling. These involve some type of soil surface manipulation and retain runoff under small-storm conditions, but water from large storms may overtop and wash out the earthen structures (Unger, 1996).

Under some conditions, it may not be practical or desirable to prevent or retain runoff. However, to control erosion under those conditions, runoff must occur at controlled, nonerosive rates. Practices that result in runoff at controlled rates include land smoothing, strip-cropping, graded furrows, graded terraces, variations of bench terraces, discontinuous parallel terraces, and land imprinting. The objective of these practices is to safely convey excess water from croplands to nearby waterways and streams (Unger, 1996).

An alternative approach to soil conservation is the modification of some soil properties responsible for the susceptibility of soil to erosion. Increasing aggregate stability at the soil surface and preventing clay dispersion are known to control seal formation, increase the infiltration rate, and reduce runoff in cultivated soils. In addition, stable aggregates at the soil surface are less susceptible to detachment by raindrop impact and to transportation by runoff water. Improving aggregate stability and preventing clay dispersion can be done by applying amendments to the soil. Gypsum and synthetic organic polymers are two types of soil amendments that have potential for controlling seal formation, runoff, and water erosion (Levy, 1996).

Organic matter improves the cohesiveness of the soil, increases its water retention capacity, promotes a stable aggregate structure, and reduces soil erosion by water. Organic material may be added as green manures, straw, or as a manure which has already undergone a high degree of fermentation (Morgan, 1995). Risse and Gilley (2001) assembled and summarized information quantifying the effects of manure application on runoff and soil loss resulting from natural precipitation events, and they developed regression equations relating reductions in runoff and soil loss to annual manure application rates. For selected locations on which manure was added annually, runoff was reduced from 1 to 68 percent, and soil loss decreased from 13 to 77 percent.

SUMMARY

Soil erosion by wind and water is a worldwide problem. Approximately 90 percent of cropland in the United States is currently losing soil above the sustainable rate. Erosion rates are even higher in many other countries. Computer models can be useful tools to assess erosion and evaluate the effect of alternative management scenarios on erosion.

The empirical wind erosion equation (WEQ) was developed in the 1960s to identify major factors influencing wind erosion and to develop wind erosion control methods. Advances in wind erosion science and the increased power of personal computers have allowed the development of a processed-based Wind Erosion Prediction System (WEPS) as a replacement for WEQ. WEPS includes submodels for erosion, hydrology, soil, crop, decomposition, and management. It is intended for planning soil conservation systems, providing environmental planning and assessment evaluations, and estimating off-site impacts of wind erosion.

The Universal Soil Loss Equation (USLE) predicts average annual soil erosion by water. It is an empirical model based on a large number of experimental data from small plots. The Water Erosion Prediction Project (WEPP) is a process-based model meant to replace USLE. It describes the processes that lead to erosion, including infiltration and runoff, soil detachment, transport, and deposition, and plant growth, senescence, and residue decomposition. The effects of tillage processes and soil consolidation are also modeled. The European Soil Erosion Model (EUROSEM) simulates erosion, transport, and deposition of sediment over the land surface by interrill and rill processes, and it simulates the effects of plant cover on rainfall interception, infiltration, flow velocity, and splash erosion. Applications of water erosion models have included the prediction of water and sediment discharge in watersheds on agricultural and military training lands, the study of flood prevention and soil conservation, and research on the influence of global greenhouse-gas emissions on soil erosion.

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