1

Introduction

Imagine a small group of processes that have operated on the land since the first rains and winds millions of years ago and in all but the coldest and driest regions. These processes are largely responsible for the shape of the Earth's land surface. They divide the land into drainage basins, sculpt the mountains and the valleys, and form the hillslopes and stream channels. They are capable of stripping the fertile topsoil from the land, topsoil that was tens, hundreds, or even thousands of years in the making. They are capable of destroying the productivity of the land in just a few years or even months, quite literally taking the food from the mouths of men, women, children, and other fauna. This small group of processes is known as *erosion and sedimentation*, and includes detachment, entrainment, transportation, and deposition of soil and other earth materials.

On the basis of its temporal and spatial ubiquity, erosion qualifies as a major, quite possibly *the* major, environmental problem worldwide. Due to its temporal and spatial ubiquity, together with its numerous impacts, erosion is an essential research topic for physical and social scientists alike. Serious efforts by farmers, miners, contractors, and the personnel of several government agencies are necessary to protect the soil by means of effective erosion-control programs and to minimize both on- and off-site damage resulting from erosion and sedimentation.

Today, the rate of soil erosion exceeds the rate of soil formation over wide areas resulting in the depletion of soil resources and productive potential (Figure 1.1). This disparity between erosion and soil-formation rates usually is the result of human activities. As the global population increases and the demands for food, shelter, and standard-of-living expectations increase, soil depletion proceeds at faster rates and over wider areas.

Figure 1.1 Accelerated erosion on agricultural lands in south-central Iowa. (Courtesy of USDA, NRCS.)

In the United States alone, about 57.3 million acres (23.2 million hectares) of fragile highly erodible cropland was determined to experience excessive erosion, and about 50.5 million acres (20.4 million hectares) of non–highly erodible cropland was determined to have erosion that exceeded the tolerable soil-loss rate [U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS), 1997b revised, 2000]. The soil-loss tolerance is the "maximum level of soil erosion that will permit a high level of crop productivity to be sustained economically and indefinitely" (Wischmeier and Smith, 1978); the utility and limitations of this concept are discussed in Chapter 8. The tragedy, of course, is that the technology exists to control erosion rates in nearly all circumstances.

During the past 30 years, many studies have documented the magnitude of soil-erosion problems, expressed as *billions* of tons of eroded soil or *billions* of dollars of erosion and sedimentation damage each year (summaries by Lal, 1994a; Morgan, 1991). Most authors acknowledge that these data are imprecise, due to the temporal and spatial variability of erosion processes, the paucity of accurate erosion measurements, extrapolation of data from small plots to continental scales, and the conversion of erosion and sedimentation rates into monetary units (Boardman, 1998; Crosson, 1995; Lal, 1994a; Osterkamp et al., 1998; Pimental et al., 1995;

Ribaudo, 1986). Nevertheless, by any measure, soil erosion is a monumental problem throughout the world, threatening ecosystems and human well-being.

The average erosion rates for very large areas misrepresents the true dimensions of erosion problems. An average value disguises the areas of low and high erosion rates. Some parts of a large area frequently experience low erosion rates that may not be problematic or may be controlled through minor and inexpensive modifications of cultural practices. Other parts of a large area often experience high erosion rates that require substantial efforts and resources to control erosion. Often, a small proportion of a land area is responsible for a large proportion of the total erosion and sediment yield. Erosion control targeted toward the areas with the highest rates can markedly reduce erosion averages.

Soil erosion is an issue where the adage "think globally, act locally," is clearly *apropos*. Think globally, because soil erosion is a common problem that has, does, and will continue to impact the global community. Act locally, because effective erosion control requires action at the hillslope, field, stream channel, and upland watershed scales.

In most cases, long-term soil productivity and long-term sustainable agriculture require soil-erosion rates that do not exceed soil-formation rates. Soil productivity is the capacity of a soil, in its normal environment, to produce a particular plant or sequence of plants under a specified management system (National Soil Erosion–Soil Productivity Research Planning Committee, 1981). Soil productivity can be maintained and even enhanced, at least in the short term, through the use of high-yield plant varieties, pesticides, and fertilizers. These practices, however, are not economically feasible in some cases, reducing farm-business profitability, and sometimes cause other environmental problems, such as water pollution due to the transport of pesticides and fertilizers in the runoff from fields. Further, the transfer of these technologies to the "developing world" often is limited by economic and other cultural conditions.

The development and management of effective erosion-control programs require a thorough understanding of erosion processes, the ability to measure and estimate erosion rates accurately, and a knowledge of the theory and practice of erosion-control techniques. The goal of this introductory soil-erosion textbook is to (1) provide a fundamental knowledge of erosion processes, measurement, estimation, and control; (2) identify sources of more detailed information; and (3) lay the foundation for a career in erosion research and soil conservation.

PHYSICAL AND ECONOMIC SIGNIFICANCE OF EROSION

Soil erosion affects the land and its inhabitants in various direct and indirect ways. In this section, the physical and economic ramifications of erosion are discussed and social issues are addressed later in the chapter.

Changes in Soil Properties

Soil properties are the product of pedogenic (soil-forming) processes, frequently modified by human activities. Properties such as material strength, infiltration capacity, and plant productivity are altered by erosion processes (Appendix A). Soils possess strength properties that largely determine the ability to resist stresses. These properties often change in the long term as the result of weathering, pedogenic processes, and decomposition of organic matter, as well as in the short term as a result of seasonal climate conditions. Accelerated erosion removes the upper layer (A-horizon) of the soil, exposing the underlying layer (B-horizon) that may possess different strength properties and, hence, different abilities to resist the stresses imposed by gravitational forces, raindrop impact, and surface runoff.

Another important property of soils is the *infiltration capacity*, defined as the maximum rate at which water enters the soil. The infiltration capacity of the soil divides precipitation into soil moisture, groundwater, and surface runoff (Appendix B). Soil moisture binds soil particles together, reducing wind erosion rates. Water flowing beneath the surface produces pore-water pressures that reduce the friction between soil particles, making the particles more susceptible to gravitational and erosive forces. Subsurface flows may emerge downslope as seepage and contribute to surface flows. Once the precipitation rate exceeds the infiltration capacity of the soil, runoff collects and flows across the land surface, generating the hydraulic forces that erode and transport sediment from hillslopes and through stream channels. The infiltration capacity of the A-horizon often is substantially higher than the infiltration capacity of the B-horizon. When erosion removes the A-horizon, exposing the

B-horizon, a precipitation event of given intensity produces greater runoff volume and velocity, due to the lower infiltration capacity, and causes higher erosion rates, depending on the susceptibility (erodibility) of the B-horizon material to erosive forces.

Soils possess physical and chemical properties that strongly influence vegetation growth. Productivity suffers from too much or too little water. Slow-draining soils may become waterlogged, akin to overwatered household plants, making the soil suitable only for hydrophytic (wetland) plant types. Fast-draining soils may not retain adequate water to support other than xerophytic (desert land) plant types. The water-holding capacity of a soil is related to the particle-size composition. Fine-textured soils possess greater surface area to which water molecules can adsorb and be stored than do coarse-textured soils. As a rule of thumb, soils composed of 70% or more sand-size particles are considered to be droughty. When fine-size particles are removed from the soil by water and wind erosion processes, the water-holding capacity of the soil decreases. The decrease in water-holding capacity adversely affects plant growth if water becomes a limiting factor. In addition, the reduction of soil depth due to erosion decreases the volume of soil involved in water and nutrient storage.

Fertility is the capacity of a soil to provide the quantities and balances of elements and compounds necessary for plant development. Plant nutrients are stored and cycled through the upper layers of soil. Removal of these layers by erosion diminishes the quantities of nutrients available for plant use. Some plant nutrients and pesticides (including insecticides, herbicides, fungicides), whether naturally occurring or applied by the farmer or reclamation specialist, are adsorbed to sediment particles and transported from the site by runoff and erosion. Figure 1.2 shows the spatial variability of potential pesticide runoff in the United States.

Economic Consequences of Erosion

The economic consequences of erosion can be examined at local (field, farm, or construction site), regional, and national scales. Changes in the physical and chemical properties of the soil affect farm-business profitability by reducing crop yields or increasing management requirements to maintain yields. According to the USDA, NRCS (1997a), soil erosion continues to threaten the productive capacity of nearly one-third of the cropland and at least one-fifth of all rangeland in the United States Soil erosion reduces crop yields by reducing soil organic matter, water-holding capacity, rooting

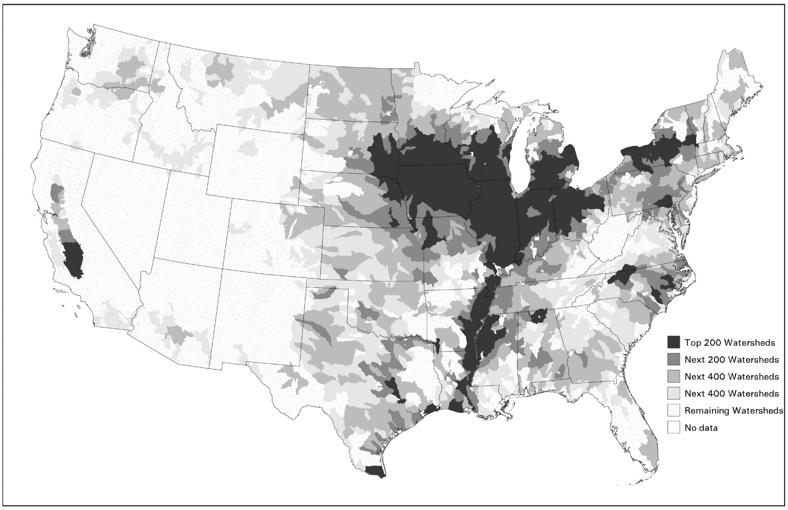


Figure 1.2 Map showing estimated potential pesticide runoff for the conterminous United States, (pounds per watershed), 1996. (Courtesy of USDA, NRCS.)

depth, and the availability of plant nutrients, as well as degrading soil structure and altering the soil texture (Weesies et al., 1994).

It has proven somewhat difficult to accurately document the relationship between soil erosion and land productivity because both soil erosion and productivity rates are influenced by numerous conditions that vary temporally and spatially. For example, Olson et al. (1994) observed that the variables complicating the relationship between soil erosion and soil productivity include (1) landscape position and hillslope components, (2) surface and subsurface water flow, (3) natural versus artificial erosion-control treatments, (4) soil properties, and (5) past and present land management. In addition, climate variability from year to year affects both soil erosion and productivity during field studies, complicating data analyses and interpretations.

Soil erosion is an insidious process that attacks the most productive topsoil layer first and may cause decreasing productivity at imperceptible rates over extended periods. Thus, the decline in soil productivity often is masked by planting high-yield crop breeds and by increasing the applications of fertilizers and pesticides where the financial resources are available to permit these investments (Follett and Stewart, 1985). Before the widespread use of commercial fertilizers, loss of topsoil reduced yields 50% or more compared to yields from soils with little topsoil loss (Weesies et al., 1994). Extensive analyses revealed that the reduction in crop yield depends on soil and climate characteristics as well as fertilization rates. Soil erosion affects farm-business profitability, in both the short and long term.

The cumulative effects of high erosion rates may have national and regional consequences. Since 1982, cropland in the United States, declined by about 11 million acres (4.5 million hectares) or 2.6%, pastureland declined by almost 12 million acres (4.9 million hectares) or 9%, and rangeland declined by about 11 million acres (4.5 million hectares) or 2.6%, while forestland increased by 3.6 million acres (1.5 million hectares) or 0.9% (USDA, NRCS, 1997b, revised 2000). Former croplands in the northeastern and southern states now support forests. Many acres (hectares) of Mississippi River bottomland forests and Great Plains grasslands are now croplands (USDA, NRCS, 1997a). In fact, there are several reasons for these land-use changes, including changes in agrobusiness economics, soil depletion due to past erosion, and the influences of erosion-control programs, in addition to competing land uses, especially urban and suburban development.

In an effort to protect soils vulnerable to water and wind erosion, the Conservation Reserve Program (CRP) was created in 1985. As of 1997, 32.7 million acres (13.2 million hectares) were enrolled in the CRP program and taken from production. The estimated average *annual* sheet and rill erosion from cultivated cropland was 3.1 tons/acre (7 metric tons/ha) per *year*, while the sheet and rill erosion from CRP land was 0.4 ton/acre (0.9 metric ton/ha) per year. Estimated average annual wind erosion from cultivated cropland was 2.5 tons/acre (5.6 metric tons/ha) per year, while wind erosion from CRP land was 0.3 ton/acre (0.7 metric ton/ha) per year (USDA, NRCS, 1997b).

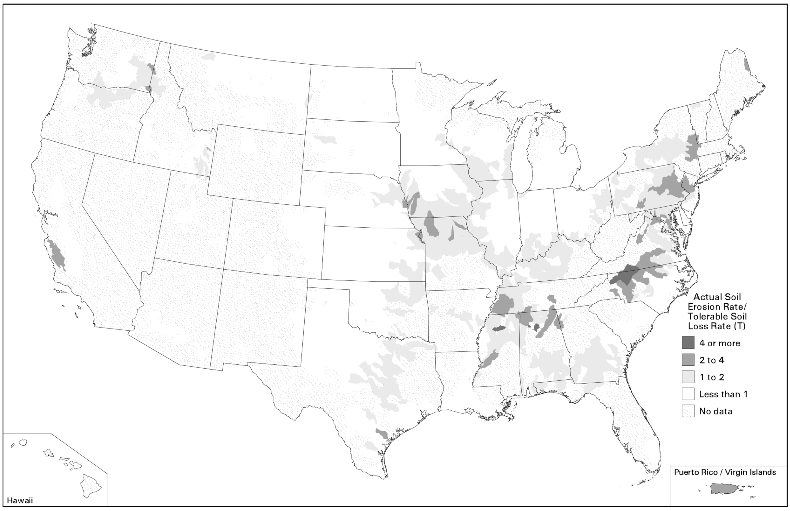
Conservation reserve programs that retire erosion-vulnerable lands from production are feasible in the United States, due to the abundance of fertile croplands coupled with the economic and technical resources to maximize productivity on other lands. Today, each acre (hectare) of cropland produces nearly three times as much food and fiber as that which was produced by that acre (hectare) in 1935 (USDA, NRCS, 1997a). As a result, the demands of the U.S. marketplace are satisfied at prices lower than those for other industrial countries. The question is whether or not high levels of productivity are sustainable through future generations. There are about 108 million acres (43.7 million hectares) of cropland in the United States where the annual soil-erosion rate exceeds the soil-loss tolerance rate (USDA, NRCS, 1997b). Figure 1.3 shows the spatial variability of cropland erosion in the United States.

The situation, however, is very different in other parts of the world. There is some evidence indicating that the world's per capita food supply has declined during the past 10 years and continues to decrease, due to the loss of land productivity resulting from excessive soil erosion combined with population growth (Pimental et al., 1995). Where land ownership is not legally established, other lands are affordable, or simply as a matter of family survival, farmers may move to new lands when the expected returns from the new land exceed those from the existing land under cultivation (Barbier and Bishop, 1995). Shifting cultivation, itself, is not the problem; in fact, it is somewhat analogous to crop rotation. Intensive land use for extended periods prior to abandonment, including prolonged intense clean-tilled crop production, and the failure to protect the land with a vegetation cover while unused, can lead to severely degraded lands that require very long periods for recovery.

In some countries, government subsidies for fertilizers, pesticides, and irrigation facilitate the realization of productivity goals, at least for the short term. The focus of this volume is erosion processes, estimation, measurement, and control rather than a review of soil-erosion problems around the world. Information concerning soil erosion in other countries can be found in Morgan (1986), Troeh et al. (1991), and numerous issues of the *Journal of Soil and Water Conservation*, among other sources.

Land disturbance resulting from mining, residential, commercial, and highway construction can accelerate erosion rates by two or more orders of magnitude, depending on the pre-disturbance land use (Toy and Hadley, 1987). During a five-month period, 0.3, 2.0, and 0.4 ton/acre (0.6, 2.4, and 1.0 metric ton/ha, respectively) of sediment was trapped in weirs placed on three mined watersheds, while during the same period no sediment was trapped in the weirs placed on nearby unmined watersheds (Curtis, 1971). Even recreational land uses that disturb the vegetation cover and the underlying soil, including off-road vehicle traffic, horseback riding and hiking, can lead to rill and gully erosion, degrade the aesthetic appeal of the land, increase maintenance costs, and increase the sediment delivered to nearby streams.

The technology to control erosion rates carries a price tag that usually increases production costs on the farm, increases land-reclamation costs at the mine, and increases water- and sediment-management costs at the construction site; all of which reduce profitability. Historically, many



(a)

(b)

Figure 1.3 Maps showing (*a*) estimated average annual soil loss by water on cultivated cropland as a proportion of the tolerable rate (*T*), 1997, and (*b*) estimated average annual soil loss by wind on cultivated cropland as a proportion of the tolerable rate (*T*), 1997. (Courtesy of USDA, NRCS.)

farmers have been reluctant to deviate from low-risk, traditional land-management practices solely for reasons of erosion control, unless it was in their best economic interest to do so. The economics of conservation practices appear to be a major reason for their acceptance or nonacceptance (Weesies et al., 1994). Long-term erosion-control goals become irrelevant when there is a family to be fed or the mortgage banker is at the door. Similarly, the mine or construction-project manager is held accountable for project costs, and commonly there are company owners, supervisors, and stockholders very interested in project profitability.

During the past three decades, new economic factors have entered into the *profitability equation*. Environmental legislation, regulations, and certification focus societal attention on short- and long-term impacts of soil erosion and sedimentation. The legislation and regulations may be enforced by substantial monetary disincentives (fines) for land- and water-quality degradation or monetary incentives to control erosion and sedimentation in the form of participation in government subsidy or insurance programs. International certification programs may restrict a producer's access to the world marketplace unless environmental standards, including erosion and sediment control standards, are established and maintained. The International Organization for Standardization (ISO) is a worldwide federation of national standards organizations from about 140 countries (www.iso.ch). ISO 14,000 standards pertain to environmental management. Certification under these standards is required to sell specific products in some European countries.

Although legislation and certification does not provide a complete solution to land degradation problems, they can link economic and erosion-control objectives, and in many cases, erosion rates have declined as a result. Sometimes, economically marginal operators are driven out of business by the added costs of environmental protection. At the state, national, or global scale, this may be considered an acceptable sacrifice for the "greater good." At the personal or family scale, it seems like a high price to pay for a small increment of environmental protection.

Wind Erosion

Although discussions of erosion often focus on water processes, wind erosion deserves specific attention. Wind erosion cannot be dismissed as a problem of the American Dust Bowl during the 1930s (Figure 1.4). Wind erosion continues to be a problem in many parts of the arid and semiarid

Figure 1.4 "Black roller" moving across the plains carrying soil blown from unprotected farmland during the Dust Bowl days of the 1930s. (Courtesy of USDA, NRCS.)

world, including much of North Africa and the Near East; parts of eastern, central, and southern Asia; the Siberian Plains; Australia, northwestern China; southern South America; and North America (Wind Erosion Research Unit, 2001). (www.weru.ksu.edu/nrcs). In the United States, wind erosion is the dominant soil problem on about 74 million acres (30 million hectares). Wind erosion causes soil-texture changes because fine particles are removed, decreases soil depth and fertility, decreases land productivity, causes abrasion of plants, automobiles, and houses, causes sedimentation in ditches and on roadways, reduces visibility along roadways, and decreases water quality. In addition, research indicates that exposure to high aerosol concentrations of particles less than $10\ \mu m$ in diameter (PM_{10}) contributes to respiratory problems in humans. Urban areas on the Columbia Plateau of eastern Washington, northern Oregon, and the Idaho Panhandle have exceeded the PM_{10} standard established under the Clean Air Act of 1990 on numerous occasions since measurements started in 1985, with several occurrences on days of obvious wind erosion on agricultural lands (Saxton et al., 1997). Although somewhat speculative, Pimental et al. (1995) estimated total wind-erosion costs at about \$9.9 billion per year for the United States—billions of dollars, each year, in one country. A comprehensive assessment of soil erosion and the development of erosion-control plans in any area requires consideration of both wind and water erosion.

Sedimentation

The sediment resulting from erosion is responsible for off-site environmental damage due to (1) sediment movement, (2) sediment storage, (3) chemicals adsorbed to sediments, and (4) the response of biota to both sediments and chemicals (Osterkamp et al., 1998). Sediment is, by far, the most common water pollutant in the United States as well as in other parts of the world. This sediment increases road-ditch maintenance costs, decreases the storage capacity and life expectancy of reservoirs, increases the cost of channel maintenance for navigation, decreases the recreational values of waterbodies, increases flood damage, and increases water treatment costs. The chemicals transported on sediment reflect regional land uses, such as fertilizers and pesticides in dominantly agricultural areas (Figure 1.2), and processing chemicals, heavy metals, and other manufacturing wastes in dominantly industrial areas. The cost of water pollution by sediment in the United States was estimated at about $16 billion per year in one recent study (Osterkamp et al., 1998), but this value was considered to be quite conservative. Another study set the total cost of erosion and sedimentation by wind and water at more than $44 billion per year (Pimental et al., 1995), but this value was considered to be too high (Crosson, 1995). The point is that the cost of erosion and sedimentation is measured in billions of dollars, each year, for the United States alone.

SOCIAL SIGNIFICANCE OF EROSION

Accelerated erosion due to human activities may first have occurred with the burning of vegetation to drive game animals, then intensified and spread geographically during the agricultural revolution, and again intensified and spread with technological developments that facilitated tillage and earthwork, including tractors, plows, disks and harrows, bulldozers, motor scrapers, road graders, and front loaders. Any activity that disrupts the vegetation cover on the land usually results in accelerated erosion rates.

An interesting history of agriculture compiled by Troeh et al. (1991) illustrates the significance of soil erosion in early civilizations. Although the actual first agricultural site may never be discovered, the ancient village of Jarmo in northern Iraq generally is considered to be the earliest (11,000 B.C.) location of cultivated agriculture. The villages in this area were situated on uplands with fertile, friable, and easily tilled silt-loam soils. It is logical to suspect that soil erosion was a problem on these sites and on these soils once the natural vegetation cover was disturbed. A common scenario emerges from the discussions by Troeh et al. (1991) concerning agriculture and soil erosion in Mesopotamia, Palestine, Phoenicia, Syria, Greece, and Italy. It appears that agriculture was first practiced on the floodplains, bottomlands, and other gently rolling, low-lying areas where erosion potentials were low. With increasing populations, the demand for food increased, causing agriculture and grazing to move up the valleysides onto steeper and more erodible hillslopes. Accelerated erosion on the hillslopes caused sedimentation on the fields and in the towns below and eventually reduced agricultural productivity. With increasing populations, the demand for fuels also increased, resulting in deforestation of hillslopes, again causing accelerated erosion rates over ever-wider areas. It seems that the citizens of Babylon lost the battle with sediment eroded from the surrounding hillslopes thousands of years ago. There undoubtedly are various factors contributing to the demise of ancient civilizations. Many agricultural and soil scientists believe that soil erosion often was a major factor, with declining agricultural productivity and increasing field and irrigation-system maintenance requirements.

Soil Erosion in the United States

In the United States, soil-erosion problems were noted during Colonial times as European farming practices were employed under North American environmental conditions. In the years that followed, advancements in agricultural practices frequently resulted in high erosion rates. New and sometimes highly erodible lands were put under the plow (Heimlich, 1985). By 1930, soil erosion by water and wind was recognized as a national problem requiring intervention at the federal level. The Soil Erosion Service was created by Congress on July 17, 1933, as a temporary public-works program that provided much-needed employment during the Great Depression, as well as the personnel for numerous erosion-control projects. In 1935, Congress transferred the agency to the U.S. Department of Agriculture and renamed it the Soil Conservation Service, later to become the National Resources Conservation Service in 1995.

Coal has been a major fuel source throughout the history of the United States In Appalachia and other regions, coal was mined without much regard to environmental degradation until state laws to regulate the industry were enacted beginning about 1930. The effectiveness of these state laws in protecting the environment varied widely, and all too often, erosion transported sediment and adsorbed contaminants to stream channels, polluting the waters and destroying the aquatic habitats. The Office of Surface Mining Reclamation and Enforcement was created by Congress on August 3, 1977 to control surface coal mining operations and insure the reclamation of lands disturbed by these operations.

Hardrock mining activities can cause the same environmental problems as coal mining. In addition, the tailings from ore processing often are highly erodible and contain heavy metals and processing chemicals that can cause serious water-pollution problems if transported into and through drainage systems. Environmental regulation of hardrock mining activities has received considerable attention in recent years (National Research Council, 1999).

As the population of the United States increased and shifted from rural to urban areas, residential, commercial, and highway construction increased dramatically. These projects also disturbed the natural land surface, increased runoff rates and volumes by rendering a proportion of the surface impervious, and at least temporarily increased erosion and sedimentation rates in streams and rivers (Wolman and Schick, 1967). Montgomery County, Maryland was among the first U.S. counties, in 1965, to enact an ordinance requiring sediment control on all new residential construction sites.

The environmental movement of the 1960s and 1970s called attention to air, land, and water degradation in all forms. Soil erosion again was recognized as a serious environmental problem, caused not just by agriculture but by virtually all land-disturbing activities. Sediment was recognized as the primary pollutant in the nation's waterways. Laws were passed at federal, state, and local levels, followed by regulations and guidelines, to control soil erosion and sediment delivery to streams and rivers. A few examples of federal legislation that seek directly or indirectly to control soil erosion include:

- National Environmental Policy Act of 1969
- Clean Water Act of 1972
- Soil and Water Conservation Act of 1977
- Surface Mining Control and Reclamation Act of 1977
- Food Security Act of 1985 ("Farm Bill")
- Clean Air Act of 1990

For the first time in U.S. history, agricultural policy linked eligibility for federal farm-program benefits to land stewardship through the 1985 Farm Bill. This act required that farmers practice soil conservation in return for commodity price supports, crop insurance, farm loans, and other program benefits (Figure 1.5). Many other countries experience similar soil-erosion problems (Troeh et al., 1991) and have enacted laws and programs in efforts to control erosion.

State and local laws tend to parallel federal laws but emphasize special state and local environmental conditions or concerns. State laws usually must be at least as stringent as federal laws in order for a state to assume

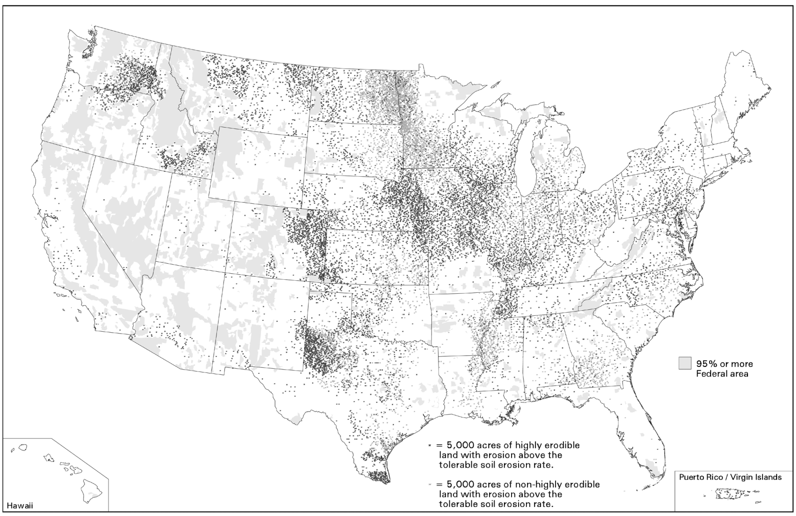


Figure 1.5 Map showing estimated excessive water and wind erosion on cropland, 1997. (Courtesy of USDA, NRCS.)

regulatory authority over activities causing land disturbance, accelerated erosion, and sedimentation.

Soil Conservation and Erosion Control

Many early civilizations recognized the relationship between accelerated erosion in their fields and the decline of agricultural productivity. Terraces appear to be among the first erosion-control practices, or perhaps the most persistent on the landscape. The Chinese, Phoenicians, Greeks, Romans, Incas, and Mayans were among those who constructed elaborate terrace systems. Vegetative cover and management have long been recognized as effective means of reducing erosion rates. Contour plowing and stripcropping have been regarded as effective erosion-control practices for many years. Crop-rotation sequences included years with complete vegetative cover on the field, such as four years of hay, two years of corn, followed by one year of wheat. The addition of manures and "night-soil" (human waste) have the combined effect of increasing productivity and reducing erosion rates. Standard agricultural conservation practices are a part of the reclamation of mine and construction sites as well.

In recent decades, erosion control has become a sophisticated science. Conservation tillage, especially no-till agriculture, reduces soil disturbance and leaves on the surface plant residues from the preceding year's crop. For sites with high erosion potential, a wide variety of erosion-control products are available, ranging from chemical soil stabilizers or binders, to hydraulically applied mulches, to nettings and mats of natural or manufactured materials, to interlocking concrete blocks for areas of concentrated flow. Most of the practices and products for the control of erosion by water also effectively control erosion by wind. Other practices, such as shelterbelts, are used specifically to reduce wind erosion.

SOIL-EROSION RESEARCH

The foundation of modern erosion control is research pertaining to the erosivity of rainfall and wind, hillslope and soil hydrology, runoff hydraulics, soil erodibility, the ability of vegetation covers and manufactured products to resist erosive forces, and the effects of management practices on both forces and resistances. This research must be conducted at various temporal and spatial scales. Temporal scales range from changes in erosion processes during a precipitation event to the potential influence of long-term climate change on erosion processes. The erosion rate and volume of sediment produced during a single design storm is important in the planning and construction of sediment basins, whereas average annual erosion rate usually is the basis for the selection of conservation practices on agricultural fields. Spatial scales range from erosion on areas no larger than a square yard (square meter) on ridges and hillslopes to the sediment discharged from entire watersheds.

The first formal erosion measurements in the United States were taken in 1912 on overgrazed rangelands in central Utah. In 1917, erosion plots were established at the University of Missouri–Columbia that are still in use today. Since the 1950s, rainfall simulation has been widely used to study erosion processes. Since the late 1960s to the present, much of the research focused on the mathematical modeling of erosion processes and rates using the accumulated field and laboratory data (Laflen et al., 1991a; Renard et al., 1991).

Formal erosion research programs at the federal level began in 1929 with the establishment of 10 soil-erosion experiment stations. In 1935, the Soil Conservation Service was formed, primarily to facilitate the transfer of erosion-control technologies from the laboratories and experimental plots to the farmer's field. In 1946, the Wind Erosion Project (now Wind Erosion Research Unit) was funded by the U.S. Congress and located at Manhattan, Kansas in cooperation with Kansas State University. In 1954, the Agricultural Research Service was created to coordinate USDA research, including soil-erosion research, and to provide technical support for the Soil Conservation Service. The National Runoff and Soil Loss Data Center, also was established in 1954 at Purdue University to assemble and consolidate for further analyses, all of the available runoff and erosion data collected throughout the United States. The National Sedimentation Laboratory was built in 1958 to study sediment transportation in streams and lake sedimentation; the mission was later expanded to include upland soil erosion and sediment transportation from agricultural-size watersheds.

Over the years, numerous university professors, their students, and government agencies throughout the world have contributed significantly to soil-erosion research, yet there is still much to be done, because erosion by water and wind have proven to be highly complex processes with rates varying in response to highly complex factors, such as weather, soil, vegetation, and land management. Today, it is possible to search the Internet for individuals, organizations, and government agencies involved in erosion research to learn of recent and current projects worldwide. Frequently, the latest reports and software can be downloaded from these Web sites. The Internet has revolutionized timely erosion-technology transfer (Appendix C).

TERMINOLOGY OF EROSION

Several scientific disciplines study erosion from somewhat different perspectives, for different reasons, and in different parts of the world. Over the years, terminology has emerged to describe erosion and related processes. Unfortunately, the terms are not employed consistently. Common terms and the definitions used in this book are discussed in Chapter 3. Types of erosion are differentiated on the basis of *location* (hillslope and channel erosion) and *agent* (water, wind, ice). Erosion and sedimentation processes include *detachment, entrainment, transportation*, and *deposition* of soil and other earth materials and may be described by traditional terms (e.g., rainsplash, sheet and rill erosion) and contemporary terms (interrill and rill erosion). *Soil loss* refers to the sediment from the eroding portion of a hillslope where overland flow occurs. *Deflation* is another term for wind erosion. *Sediment yield* and *sediment delivery* express the rate or amount of sediment transported to a point of measurement, at the base of a hillslope, the boundary of a field, in a stream channel, or at the mouth of a watershed. The term *denudation* usually pertains to large areas such as landscapes and drainage basins and refers to the average decrease in land-surface elevation during long periods of time, ignoring the variability of erosion rates within the large area. Soil scientists define the characteristics of a "soil" carefully and specifically. In this book, the word *soil* often is used in a broad context to refer to any soil-like material subjected to erosion processes, sometimes a true soil, sometimes a manufactured soil (minesoil), sometimes the alluvium of a floodplain. Students, instructors, scientists, and erosion-control specialists should exercise care in using these terms, in accordance with the conventions of their discipline, but remain aware that connotations associated with the terminology may differ among disciplines.

Natural (Geologic) Erosion

Erosion processes have operated for millions of years, as evidenced by the prevalence and thickness of sedimentary rocks at the Earth's surface. Natural erosion rates prevail under natural or undisturbed environmental conditions. Such erosion rates also are called *geologic rates*. Under natural erosion rates, soil properties and soil profiles usually develop to approach an equilibrium condition (Nikiforoff, 1942). A fully developed soil profile is sometimes taken as evidence that erosion is occurring at a natural rate. It is possible, however, for high erosion rates to occur in response to natural events such as fires or plant disease, extraordinary rainstorms, or congregations of wildlife that disturb vegetation covers and compact soils.

Accelerated (Anthropic, Human-Induced) Erosion

Under disturbed environmental conditions, water and wind erosion rates may be accelerated by several orders of magnitude. Such erosion rates also are known as *anthropic*, or *human-induced rates*. Soil formation generally cannot keep pace with soil removal. A degraded soil profile, with the B- or C- horizon at the surface, often is taken as evidence that erosion is occurring, or has occurred, at an accelerated rate. The land may be dissected by rills and gullies. Geologic strata may become exposed at the surface. Natural and cultivated vegetation productivity decrease sharply. Sediment is washed into ponds, lakes, and reservoirs or accumulates in channels to be transported by high flows. Agricultural chemicals or toxic materials are adsorbed and transported on the sediments. High sediment concentrations and chemical loads may adversely affect aquatic flora and fauna.

Usually, accelerated erosion is the result of human activities that disturb vegetation covers, expose soils, and increase slope steepness. Hence, accelerated erosion and its consequences largely are avoidable and manageable with proper planning and scheduling prior to land disturbance; implementation of water-, erosion-, and sediment-control practices during active disturbance; and land reclamation following disturbance. Since 1982, erosion on cropland and CRP land in the United States has decreased by about 38% (USDA, NRCS, 1997b).

DEVELOPMENT OF LANDSCAPES: A CONTEXT FOR EROSION

The landscapes of the Earth are the product of both internal and external processes. Internal processes originate within the Earth, add to the landmass above sea level; raise landmasses, increasing their potential energy;

and create surfaces upon which external processes operate. The enormous forces generated by these internal processes are manifested in earthquakes, volcanic eruptions, and folding and faulting of geologic strata. Internal processes are responsible for the large-scale (large-area) features of the Earth's surface, the positions of the ocean basins and continents, the rise and fall of broad structural mountain ranges and basins, and the deformation and tilting of strata within ranges.

External processes originate at or near the Earth's surface and work to level it by lowering the higher elevations and raising the lower elevations. There are four types of external processes: (1) rock weathering, (2) mass movement, (3) erosion, and (4) deposition. Rock-weathering processes are separated into two categories based on the changes in rocks and minerals. Physical-weathering processes result in the disintegration of rocks without changes in mineral chemistry. Chemical-weathering processes result in the decomposition of the minerals composing rocks.

Weathering processes substantially reduce the strength of rocks. The physical and chemical bonds between particles and compounds are greatly weakened. Gravitational forces produce shear stresses within the weathering mass. Eventually, the shear stresses exceed strengths, and mass movement occurs. Mass movements often produce hummocky, heterogeneous masses of earth and rock material near the downslope termini of hillslopes, referred to as *colluvium*. Lowering of the land surface by mass-movement processes is known as *mass wasting*.

Water, wind, or ice passing across land surfaces generate shear stresses within earth materials. As defined previously, erosion and sedimentation is the detachment, entrainment, transportation, deposition of soil and other earth materials. Sediment is the product of erosion.

The agents of erosion move sediment until the transport capacity of the flow is reached. Eventually, the transport capacity decreases, usually due to decreasing flow velocity. As transport capacity decreases, sediment in excess of the transport capacity is deposited. Sediments eroded, transported, sorted by particle size and density, and deposited by flowing water are known as *alluvium*. Only about 10% of the sediment eroded by water completes the journey to the sea. The remaining 90% of the sediment is deposited on hillslopes, on floodplains, and in lakes and reservoirs (Mead and Parker, 1985). Figure 1.6 shows the spatial variability in the amount of sediment delivered to streams in the United States.

Theoretically, land surfaces tend to become broad, virtually featureless plains. But usually, this is not what we see because internal and external

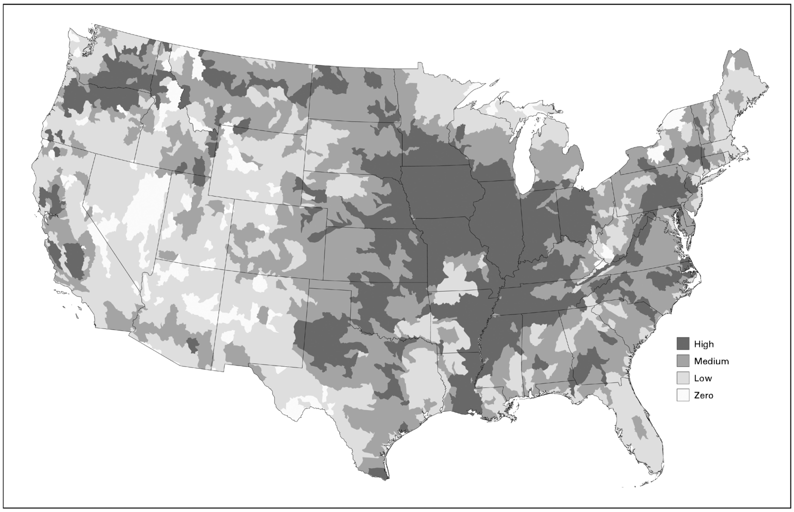


Figure 1.6 Map showing estimated sediment delivered to streams (tons), 1996. (Courtesy of USDA, NRCS.)

processes are constantly in action, varying in time and space. Topography is the current status of the interaction between internal and external processes. Most landscapes reflect the work of both past and present processes.

Erosion, then, is only one process group shaping the Earth's surface. It is, however, a very significant process group because it affects human welfare directly and indirectly and responds to human activities with increasing or decreasing rates. Throughout the remainder of this book we focus on upland erosion by water and wind. Most of the discussion centers on hillslope erosion, with due consideration to erosion in small channels. We believe that *in situ* weathering and mass wasting due to gravitational forces are separate and distinct processes.

SUMMARY

Erosion includes physical, economic, and social dimensions. During the past 100 years, most research centered on the physical processes. Again in recent years, as during the 1930s, economic and social issues have been addressed in erosion research. The conservation journals of the past decade contain articles examining the economics of erosion and erosion control, including the (1) cost-benefit and economic risks associated with various practices, (2) on- and off-site erosion costs, (3) economic impact of compliance with conservation and erosion control laws, and (4) soil erosion and crop productivity. Other articles address social issues, including the (1) attitudes and perceptions concerning soil conservation, erosion control, and compliance with conservation laws, (2) land-use planning for soil conservation and erosion control, (3) translating science into laws and policies, (4) soil-conservation education programs, (5) family factors in conservation-practice adoption, and (6) total-quality-management concepts applied to erosion control.

Environmental awareness, backed by national, state, and local legislation, regulation, and guidelines, created new industries in environmental assessment and erosion control. Industry magazines and trade shows display an astonishing array of erosion-control equipment and products, as well as advertisements for professional consulting companies. There is a professional international erosion-control association with several hundred members. Several countries have professional land-reclamation societies. Professional certification is available for erosion-and sediment-control experts, and the possibility of interdisciplinary, university-level, erosion- and sediment-control degree programs have been discussed by a professional erosion-control association. Erosion control is big business that translates into employment opportunities.

We take a somewhat nontraditional approach for an introductory soil-erosion textbook. First, the central concept is that the soil-erosion rate is a function of the soil-particle detachment rate and the soil-particle transportation rate. Hence, the types of erosion, the manner in which they operate, the principles of erosion prediction, and the principles of erosion control are examined in terms of particle detachment and transportation. Second, the interrill–rill concept provides the basis for the discussion of upland erosion processes. There are distinct differences in the erosion processes of interrill and rill areas although these processes are spatially linked. The interrill–rill concept has proven to be very useful in the development of erosion-prediction models and the development of erosion-control plans.

The underlying premise of the book is that a thorough understanding of erosion processes is the foundation for using and developing erosion-prediction models, selecting appropriate erosion measurement techniques for particular research designs, and selecting the best management practices for erosion control. This knowledge also provides a foundation for effective soil-erosion laws, regulations, and policies. Understanding the processes even helps us to understand the attitudes, perceptions, and economics surrounding soil conservation and erosion control. Imagine a small group of processes that qualifies as a major environmental problem worldwide. Imagine that you are a part of the solution.

SUGGESTED READINGS

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