15 Soil Erosion: A Food and Environmental Threat

The loss of soil from land surfaces by erosion is widespread globally and adversely affects the productivity of all natural ecosystems as well as agricultural, forest, and rangeland ecosystems (Lal and Stewart, 1990; Pimentel, 1993; Pimentel et al., 1995; Pimentel and Kounang, 1998). Concurrent with the escalating human population, soil erosion, water availability, energy, and loss of biodiversity rank as the prime environmental problems throughout the world.

Future world populations will require ever-increasing food supplies. Consider that more than 99.7% of human food comes from the land (FAO, 1998), while less than 0.3% comes from oceans and other aquatic ecosystems. Maintaining and augmenting the world food supply basically depends on the productivity and quality of all soils.

The changes inflicted on soils by human-induced erosion over many years are significant and have resulted in valuable land becoming unproductive and often eventually abandoned (Pimentel et al., 1995; Young, 1998). Simply put, soil erosion diminishes soil quality and thereby reduces the productivity of natural, agricultural, and forest ecosystems (Pimentel and Kounang, 1998; Pimentel, 2001). In addition, the valuable diversity of plants, animals, and microbes in the soil is damaged (Pimentel et al., 1995).

In this study, the diverse factors that cause soil erosion are evaluated. The extent of damage associated with soil erosion is analyzed, with emphasis on the impact these may have on future human food security as well as the natural environment.

CAUSES OF EROSION

Erosion occurs when soil is left exposed to rain or wind energy. Raindrops hit exposed soil with great energy and easily dislodge the soil particles from the surface. In this way, raindrops remove a thin film of soil from the land surface and create what is termed *sheet* erosion. This erosion is the dominant form of soil degradation (Troeh et al., 1991; Oldeman, 1997). The impact of soil erosion is intensified on sloping land, where often more than half of the surface soil is carried away as the water splashes downhill into valleys and waterways.

Wind energy also has great power to dislodge surface soil particles, and transport them great distances. A dramatic example of this was the wind erosion in Kansas during the winter of 1995–1996, when it was relatively dry and windy. Then approximately 65 t/ha was eroded from this valuable cropland during one winter (Figure 15.1). Wind energy is strong enough to propel soil particles thousands of miles. This is illustrated in the photograph by NASA (Figure 15.2) which shows a cloud of soil being blown from the African Continent to the South and North American continents.

FIGURE 15.1 About 50 mm of soil blown from cropland in Kansas during the winter of 1995–1996. (E.L. Skidmore, USDA, Manhattan, KS. Photo, spring 1996.)

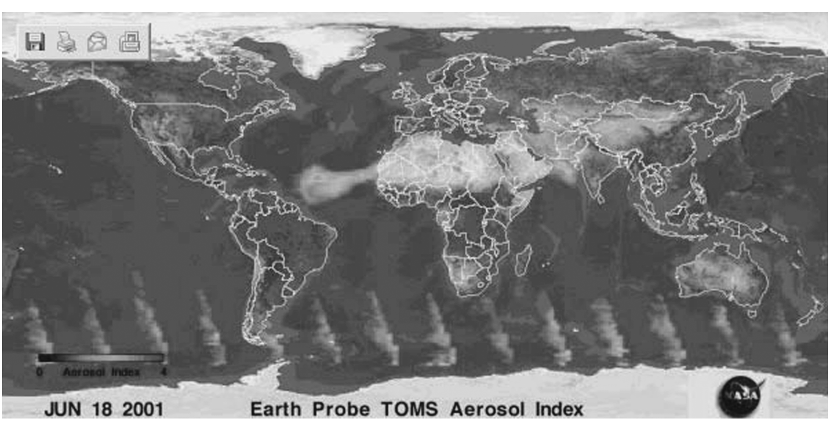

FIGURE 15.2 Cloud of soil from Africa being blown across the Atlantic Ocean. (Imagery by SeaWIFS Project, NASA/Goddard Space Flight Center and ORBIMAGE, 2000.)

Soil Structure

Soil structure influences the ease with which it can be eroded. Soils with medium to fine texture, low organic matter content, and weak structural development are most easily eroded (Bajracharya and Lal, 1992). Typically these soils have low water infiltration rates and, therefore, are subject to high rates of water erosion and the soil particles are easily displaced by wind energy.

The Role of Vegetative Cover

Land areas covered by plant biomass, living or dead, are more protected and experience relatively little soil erosion because raindrop and wind energy are dissipated by the biomass layer and the topsoil is held by the biomass (SWAG, 2002; Agriculture California, 2002). For example, in Utah and Montana, as the amount of ground cover decreased from 100% to less than 1%, erosion rates increased approximately 200 times (Trimble and Mendel, 1995).

In forested areas, a minimum of 60% forest cover is necessary to prevent serious soil erosion and landslides (Singh and Kaur, 1989; Haigh et al., 1995; Forest Conservation Act, 2002). The extensive removal of forests for crops and pastures is followed by extensive soil erosion.

Loss of soil vegetative cover is especially widespread in developing countries where populations are large, and agricultural practices are often inadequate to protect topsoils. In addition, cooking and heating there frequently depends on the burning of harvested crop residues for fuel. For example, about 60% of crop residues in China and 90% in Bangladesh routinely are stripped from the land and burned for fuel (Wen, 1993). In areas where fuelwood and other biomass are scarce, even the roots of grasses and shrubs are collected and burned (McLaughlin, 1991). All these practices leave the soil barren and fully exposed to rain and wind forces of erosion.

Land Topography

The topography of a given landscape, its rainfall or wind and exposure all combine to influence its susceptibility to erosion. In the Philippines, where more than 58% of the land has a slope of greater than 11%, and in Jamaica, where 52% of the land has a slope greater than 20%, soil erosion rates as high as 400 t/ha/year have been reported (Lal and Stewart, 1990). Erosion rates are high especially on marginal and steep lands that have been converted from forests to agriculture to replace the already eroded, unproductive cropland (Lal and Stewart, 1990). In addition, under arid conditions and with relatively strong winds as much as 5600 t/ha/year of soil has been reported lost in an arid region of India (Gupta and Raina, 1996).

Other Soil Disturbances

Although world agricultural production accounts for about three-quarters of the soil erosion worldwide, erosion also occurs whenever humans remove vegetative cover (Lal and Stewart, 1990; FAO, 2002). The construction of roads, parking lots, and buildings are examples of this problem. Although the rate of erosion from construction sites may range from 20 to 500 t/ha/year, erosion associated with construction especially is relatively brief, generally lasting only while the land surface is disturbed. Then once the land surface is seeded to grass or vegetation regrows naturally, erosion decreases (IECA, 1991). However, if the soil remains covered by buildings, parking lots, and roads, the area is lost for vegetation production and water runoff in adjacent areas increases.

Natural ecosystems also suffer erosion losses. This is especially evident along stream banks, where erosion occurs naturally from the powerful action of adjacent moving water. Increased soil losses occur on steep slopes (30% or more), when a stream cuts through adjacent land. Even on relatively flat land with only a 2% slope, streambanks are eroded, especially during heavy rains and flooding. There too, the presence of cattle in and around streams further increases streambank erosion. For example, a Wisconsin stream area inhabited by cattle lost about 60 t/year of soil along each kilometer of stream length (Trimble, 1994; Trimble and Mendel, 1995).

Soil erosion accompanies landslides and earthquakes (Bruijnzeel, 1990; McTainish and Boughton, 1993). Landslides, in which layers of soil are dislodged and move downhill, usually are associated with diverse human activities, such as the construction of roads and buildings, and the removal of forests. Overall, the erosion impact from earthquakes is comparatively minimal mainly because these events are relatively rare. However, when earthquakes occur, massive amounts of soil, including crops and forests, are affected in hillsides and in surrounding areas.

ASSESSING SOIL EROSION

Although soil erosion has been taking place very slowly in natural ecosystems throughout geologic time, its cumulative impacts on soil quality over billions of years have been significant. Worldwide, erosion rates range from a low of 0.001 to 2 t/ha/year on relatively flat land with grass or forest cover to rates ranging from 1 to 5 t/ha/year in mountainous regions with normal vegetative cover (Patric, 2002). Yet, even low rates of erosion sustained over billions of years result in the displacement of enormous quantities of soil. For example, over a period of 100 years at an erosion loss rate of 2 t/ha/year on 10 ha, erosion will deposit the soil equivalent of about 1 ha of land with a soil depth of 15 cm. In addition, eroded soil frequently accumulates in valleys forming vast alluvial plains. The large deltas of the world, such as those of the Nile and the Mississippi, are the result of centuries of erosion (Solliday, 1997).

Myers (1993) reports that approximately 75 billion tons of fertile soil are lost from world agricultural systems each year, with much less erosion occurring in natural ecosystems. In fact, the 75 billion tons is probably a conservative value. Soil scientists Lal and Stewart (1990) and Wen (1997) report 6.6 billion tons of soil per year are lost in India and 5.5 billion tons are lost annually in China. Considering these two countries together occupy only 13% of the world's total land area, the estimated 75 billion tons of soil lost per year worldwide is conservative. The amount of soil lost in the United States is estimated to be about 3 billion tons per year (Carnell, 2001).

LOSS OF PRODUCTIVITY IN MANAGED ECOSYSTEMS

Approximately 50% of the Earth's land surface is devoted to agriculture; of this, about one-third is used for crops and two-thirds as grazing lands (USDA, 2001). Forests occupy about 20% of the land area (WRI, 1997). Of these two areas, cropland is more susceptible to erosion because of frequent cultivation of the soils and the vegetation is often removed before crops are planted. This practice exposes the soil to wind and rain energy. In addition, cropland is often left without vegetation between plantings. This practice intensifies erosion on agricultural land, which is estimated to be 75 times greater than erosion in natural forest areas (Myers, 1993).

WORLDWIDE CROPLAND

Currently, about 80% of the world's agricultural land suffers moderate to severe erosion, while 10% experiences slight erosion (Pimentel, 1993; Speth, 1994; Lal, 1994). Worldwide, erosion on cropland averages about 30 t/ha/year and ranges from 0.5 to 400 t/ha/year (Pimentel et al., 1995). As a result of soil erosion, during the last 40 years about 30% of the world's arable land has become unproductive and much of that has been abandoned for agricultural use (WRI, 1994; Kendall and Pimentel, 1994).

The nearly 1.5 billion ha of world arable land now under cultivation for crop production are almost equal in area to the amount of arable land (2 billion ha) that has been abandoned by humans since farming began (Lal, 1990, 1994). Such land, once biologically and economically productive, now not only produces little biomass but also has lost considerable diversity of the plants, animals, and microbes that it once supported (Pimentel et al., 1992; Heywood, 1995).

Each year an estimated 10 million ha of cropland worldwide are abandoned due to lack of productivity caused by soil erosion (Faeth and Crosson, 1994). Worldwide, soil erosion losses are highest in the agroecosystems of Asia, Africa, and South America, averaging 30–40 t/ha/year of soil loss (Taddese, 2001). In developing countries, soil erosion is particularly severe on small farms that are often located on marginal lands where the soil quality is poor and the topography is frequently steep. In addition, the poor farmers tend to raise row crops, such as corn. Row crops are highly susceptible to erosion because the vegetation does not cover the entire soil surface (Southgate and Whitaker, 1992; Stone and Moore, 1997). For example, in the Sierra Region of Ecuador, 60% of the cropland was abandoned because erosion and inappropriate agricultural practices left the land devastated by water and wind erosion (Southgate and Whitaker, 1992). Similar problems are evident in the Amazonian region of South America, especially where vast forested areas are being cleared to provide more land for crops and livestock production.

U.S. CROPLAND

The lowest erosion rates on cropland occur in the United States and Europe where they average about 10 t/ha/year (USDA, 2000a,b). However, these low rates of erosion greatly exceed the average rate of natural soil formation from the parent material; under agricultural conditions that range from 0.5 to 1 t/ha/year (Troeh and Thompson, 1993; Lal, 1994; Pimentel et al., 1995; Young, 1998; Sundquist, 2000).

This means that 90% of U.S. cropland is now losing soil faster than its sustainable replacement rate (USDA, 2000a,b).

Soil erosion is severe in some of the most productive agricultural ecosystems in the United States. For instance, one-half of the fertile topsoil of Iowa has been lost by erosion during the last 150 years of farming because of erosion (Risser, 1981; Klee, 1991). These high rates of erosion continue there at a rate of about 30 t/ha/year, because of the rolling topography and type of agriculture practiced (USDA, 1989). Similarly, 40% of the rich soil of the Palouse region in the northwestern United States has been lost during the past 100 years of cultivation (Ebbert and Roe, 1998). In both these regions, intensive agriculture is employed and mono-cultural plantings are common. Also, many of these fields are left unplanted during the late fall and winter months, further exposing the soil to erosion. Yearly in the United States, several thousand hectares of valuable cropland are abandoned because rain and wind erosion has made them unproductive (World Problems, 1999).

The economic impact of soil erosion is significant. Uri (2001) estimates that soil erosion in the United States costs the nation about $37.6 billion each year in loss of productivity.

Pasture and Range Land

In contrast to the average soil loss of 10 t/ha/year from U.S. cropland, U.S. pastures lose about 6 t/ha/year (NAS, 2003). However, erosion rates on pastures intensify whenever overgrazing is allowed to occur on the pastures. Even in the United States, about 75% of non-Federal lands require conservation treatments to improve grazing pressures (Johnson, 1995). More than half of the rangelands, including those on non-Federal and Federal lands, are now overgrazed and have become subject to high erosion rates (Bailey, 1996; Campbell, 1998).

Although erosion rates on U.S. cropland have decreased during the past two decades, erosion rates on rangelands remain relatively high or about 6 t/ha/year (NAS, 2003). High erosion rates are typical on more than half of the world's rangelands (WRI, 1994). In many developing countries, heavy grazing by sheep and goats has removed most of the vegetative cover, exposing the soil to severe erosion. In Africa, about 80% of the pasture and rangeland areas are seriously eroded and degraded by soil erosion (UN-NADAF, 1996). The prime causes of this are overgrazing and the practice of removing crop residues for cooking fuel.

Forest Land

In stable forest ecosystems, where soil is protected by vegetation, erosion rates are relatively low, ranging from only 0.004 to 0.05 t/ha/year (Roose, 1988; Lal, 1994). Tree leaves and branches not only intercept and diminish rain and wind energy, but also cover the soil under the trees to further protect the soil. However, this changes dramatically when forests are cleared for crop production or pasture (Daily, 1996). For example, in Ecuador, the Ministry of Agriculture and Livestock reported that 84% of the soils in the hilly, forested northeastern part of the country should never have been cleared for pastures because of the high vulnerability of the soils to erosion, their limited fertility, and the overall poor soil type that resulted (Southgate and Whitaker, 1992).

EFFECTS OF EROSION ON TERRESTRIAL ECOSYSTEMS

Soil erosion reduces the productivity of terrestrial ecosystems. In order of importance, soil erosion increases water runoff thereby decreasing the water infiltration and the water-storage capacity of the soil (Troeh et al., 1991; Pimentel et al., 1995; Jones et al., 1997). Also, during the erosion process organic matter and essential plant nutrients are removed from the soil and the soil depth is reduced. These changes not only inhibit vegetative growth, but reduce the presence of valuable biota and the overall biodiversity in the soil (Troeh et al., 1991; Pimentel et al., 1995). As these factors interact with one another, it is almost impossible to separate the specific impacts of one factor from another. For example, the loss of soil organic matter increases water runoff, which reduces water-storage capacity, which diminishes nutrient levels in the soil and also reduces the natural biota biomass and the biodiversity of ecosystems (Lal and Stewart, 1990; Jones et al., 1997).

WATER AVAILABILITY

Water is a prime limiting factor of productivity in all terrestrial ecosystems because all vegetation requires enormous quantities of water for its growth and for the production of fruit (Falkenmark, 1989; Pimentel et al., 1997). For instance, 1 ha of corn or wheat will transpire more than 5–7 million L of water each growing season (Klocke et al., 1996; Pimentel et al., 1997) and lose an additional 2 million L of water by evaporation from the soil (Donahue et al., 1990; Pimentel et al., 1997). During erosion by rainfall, the amount of water runoff significantly increases, with less water entering the soil, and less water available to support the growing vegetation.

In contrast to uneroded soils, moderately eroded soils absorb from 10 to 300 mm less water per hectare per year from rainfall. This represents a decrease of 7%–44% in the amount of water available for vegetation growth (Wendt et al., 1986; Murphee and McGregor, 1991). A water runoff rate of about 30% of total rainfall of 800 mm can result in significant water shortages for crops, like corn, and ultimately low crop yields.

When soil water availability for an agricultural ecosystem is reduced from 20% to 40% in the soil, plant biomass productivity is reduced from 10% to 25% depending also on total rainfall, soil type, slope, and other factors (Evans et al., 1997). Major reductions in plant biomass not only diminish crop yields, but adversely affect the overall species diversity within the ecosystem (Heywood, 1995; Walsh and Rowe, 2001).

NUTRIENT LOSS

Eroded soil carries away vital plant nutrients such as nitrogen, phosphorus, potassium, and calcium. Typically, eroding soil contains about three times more nutrients than are left in the remaining soil (Young, 1989). A ton of fertile topsoil averages 1–6 kg of nitrogen, 1–3 kg of phosphorus, and 2–30 kg of potassium, whereas the soil on eroded land has average nitrogen levels of only 0.1–0.5 kg/t (Troeh et al., 1991).

When nutrient resources are so depleted by erosion, plant growth is stunted and overall productivity declines (Lal and Stewart, 1990; Pimentel et al., 1995). Nutrient deficient soils produce 15%–30% lower crop yields than uneroded soils (Olson and Nizeyimana, 1988; Schertz et al., 1989; Langdale et al., 1992).

To offset the nutrient losses erosion inflicts on crop production, large quantities of fertilizers are often applied. Troeh et al. (1991) estimate that the lost soil nutrients cost U.S. agriculture $20 billion annually. If the soil base is relatively deep, about 300 mm, and if only from 10 to 20 t of soil are lost per hectare per year, the lost nutrients can be replaced with the application of commercial fertilizers or livestock manure (Pimentel et al., 1995). However, this replacement strategy is expensive for the farmer and nation and usually not affordable by poor farmers. Not only are the fertilizer inputs fossil-energy dependent, but these chemicals can also harm human health and pollute the environment (NAS, 2003).

Soil Organic Matter

Fertile soils typically contain about 100 tons of organic matter per hectare (or 4% of the total soil weight) (Follett et al., 1987; Young, 1990; Sundquist, 2000). About 95% of the soil nitrogen and 25%–50% of the phosphorus are contained in the soil organic matter (Allison, 1973). Because most of the soil organic matter is found close to the soil surface as decaying leaves and stems, erosion significantly decreases soil organic matter. Both wind and water erosion selectively remove the fine organic particles in the soil, leaving behind large soil particles and stones. Several studies have demonstrated that the soil removed by either erosion is 1.3–5 times richer in organic matter than the remaining soil left behind (Allison, 1973; Lal and Stewart, 1990). For example, the reduction of soil organic matter from 1.4% to 0.9% lowered the yield potential for grain by 50% (Libert, 1995; Sundquist, 2000).

Soil organic matter is a valuable resource because it facilitates the formation of soil aggregates and thereby increases soil porosity. The soil organic matter improves soil structure, which in turn facilitates water infiltration and ultimately the overall productivity of the soil (Langdale et al., 1992). In addition, organic matter aids cation exchange, enhances plant root growth, and stimulates the increase of important soil biota (Allison, 1973; Wardle et al., 2004).

Once the organic matter layer is depleted, the productivity of our ecosystem, as measured by plant biomass, declines both because of the degraded soil structure and the depletion of nutrients contained in the organic matter. In addition to low yields, the total biomass of the biota and overall biodiversity of these ecosystems are substantially reduced (Heywood, 1995; Walsh and Rowe, 2001; Lazaroff, 2001).

Collectively and independently the diverse impacts of erosion reduce crop biomass, both because of degraded soil structure and nutrient depletion. For example, erosion reduced corn productivity by 9%–18% in Indiana, 0%–24% in Illinois and Indiana, 25%–65% in the southern Piedmont of Georgia, and 21% in Michigan (Olson and Nizeyimana, 1988; Mokma and Sietz, 1992; Weesies et al., 1994). In the Philippines over the past 15 years, erosion caused declines in corn production by as much as 80% (Dregne, 1992).

Soil Depth

Growing plants require soils of adequate depth in which to extend their roots. Various soil biota, like earthworms, also require a specific soil depth (Pimentel et al., 1995; Wardle et al., 2004). Thus, when soil depth is substantially reduced by erosion from 30 cm to less than 1 cm, plant root space is minimal, and plant production is significantly reduced.

BIOMASS AND BIODIVERSITY

The biological diversity existing in any ecosystem is related directly to the amount of living and nonliving organic matter present in the ecosystem (Wright, 1990; Heywood, 1995; Walsh and Rowe, 2001; Lazaroff, 2001; Wardle et al., 2004). As mentioned, by diminishing soil organic matter and soil quality, erosion reduces overall biomass and productivity. Ultimately, this has a profound effect on the diversity of plants, animals, and microbes present in an entire ecosystem.

Numerous positive associations have been established between biomass abundance and species diversity (Elton, 1927; Odum, 1978; Sugden and Rands, 1990; M. Giampietro, 1997, personal communication, Insituto Nazionale della Nutrizione, Rome, Italy). Vegetation is the main component of ecosystem biomass and provides the vital resources required both by animals and microbes for their survival. This relationship is summarized in Table 15.1.

Along with plants and animals, microbes are a vital component of the soil and constitute a large percentage of the soil biomass. One square meter of soil may support about 200,000 arthropods and enchytraeids, plus billions of microbes (Wood, 1989; Lee and Foster, 1991). A hectare of productive soil may have a biomass of invertebrates and microbes weighing up to 10,000 kg/ha (Table 15.1). In addition, soil bacteria and fungi add 4000–5000 species and in this way contribute significantly to the biodiversity especially in moist, organic forest soils (Heywood, 1995).

Erosion rates that are 10–20 times above the sustainability rate (soil formation rates of less than 0.5 to 1 t/ha/year) decrease the diversity and abundance of soil organisms (Atlavinyte, 1965). In contrast, agricultural practices that control erosion and maintain adequate soil organic matter favor the proliferation of soil biota (Reid, 1985; FAO, 2001).

TABLE 15.1
Biomass of Various Organisms per Hectare in a Temperate Region Pasture (Pimentel et al., 1992)

Organism	Biomass (kg fresh weight)
Plants	20,000
Fungi	4,000
Bacteria	3,000
Arthropods	1,000
Annelids	1,320
Protozoa	380
Algae	200
Nematodes	120
Mammals	1.2
Birds	0.3

The application of organic matter or manure also enhances the biodiversity in soil (Agriculture Canada, 2002; IFPRI, 2002). Species diversity of macrofauna (mostly arthropods) increased by 16% when organic manure was added to experimental wheat plots in the former USSR (Bohac and Pokarzhevsky, 1987). Similarly, species diversity of macrofauna (mostly arthropods) more than doubled when organic manure was added to grassland plots in Japan (Kitazawa and Kitazawa, 1980), and increased 10-fold in Hungarian agricultural land (Olah-Zsupos and Helmeczi, 1987).

The relationship between biomass and biodiversity was confirmed in field experiments with collards (Brassicae) in which arthropod species diversity rose fourfold in the experimental plots with the highest collard biomass compared with that in control collard plots (Pimentel and Warneke, 1989). Reports suggest that when biomass was increased threefold, the number of species increased 16-fold (Ecology, 2002) In a study of bird populations, a strong correlation between plant biomass productivity and bird species diversity was reported when a 100-fold increase in plant biomass yielded a 10-fold increase in bird diversity (Wright, 1990).

Soil erosion has indirect effects on ecosystems that may be nearly as damaging as the direct effects of reducing plant biomass productivity. For example, Tilman and Downing (1994) found that the stability and biodiversity of grasslands were significantly decreased when plant species reduction occurred. They reported that as plant species richness decreased from 25 species to 5 or less species, the grassland became less resistant to drought. The total amount of biomass declined to one fourth of the high level. The overall result was that the grassland was more susceptible to drought conditions and required more time to recover its productivity than when an abundance of plant species was present.

Sometimes soil erosion causes the loss of a keystone species, and its absence may have a cascading effect on the survival of a wide array of other species within the ecosystem. Species that act as keystone species include the dominant plant types, such as oaks, that maintain the biomass productivity and integrity of the ecosystem; predators and parasites that control the feeding pressure of some organisms on major plants; pollinators of various vital plants in the ecosystem; seed dispersers; as well as the plants and animals that provide a habitat required by other essential species, like biological nitrogen-fixers (Heywood, 1995; Daily, 1996). Thus, in diverse ways, the normal activities within an ecosystem may be interrupted when populations of keystone species are significantly altered. The damages inflicted can be severe especially in agroecosystems when, for instance, the numbers of pollinators are drastically reduced or even eliminated and there is little or no reproduction in the plants (Pimentel et al., 1997).

Soil biota perform many beneficial activities that improve soil quality and ultimately its productivity (Witt, 1997; FAO, 2001; Sugden et al., 2004). For example, soil biota recycle basic nutrients required by plants for their growth (Pimentel et al., 1995). In addition, the tunneling and burrowing activities of earthworms and other soil biota enhance productivity by increasing water infiltration into the soil (Witt, 1997). Earthworms, for instance, may produce up to 220 tunnel openings per square meter (3–5 mm in diameter). These channels enable water to infiltrate rapidly into the soil (Anderson, 1988; Edwards and Bater, 1992).

Other soil biota also contribute to soil formation and productivity by mixing the soil components, enhancing aggregate stability, and preventing soil crusting.

This churning and mixing of the upper soil redistributes nutrients, aerates the soil, exposes soil to the climate for soil formation, and increases infiltration rates, thus making the soil favorable for increased soil formation and plant productivity. Earthworms bring between 10 and 500 t/ha/year of soil from underground to the soil surface (Lavelle, 1983; Lee, 1985), while some insects, like ants, may bring 34 t/ha/year of soil to the surface (Zacharias and Grube, 1984; Lockaby and Adams, 1985; Hawkins, 2002). In arid regions, species, like the Negev desert snail, *Euchordrus* spp., also help form soil by consuming lichens and the rocks on which the lichens are growing (Shachak et al., 1995). This snail activity helps form about 1000 kg of soil per hectare per year, which is equal to the annual soil formation rate by wind-borne deposits.

SEDIMENTS AND WIND BLOWN SOIL PARTICLES

Beyond damages to rainfed agricultural and forestry ecosystems, the effects of erosion reach far into surrounding environments (Gray and Leiser, 1989; FEMAT, 1993; Ziemer, 1998).

For instance, large amounts of eroded soil are deposited in streams, lakes, and other ecosystems. The USDA (1989) reports that 60% of the water-eroded soil ends up in U.S. streams. Similarly in China, approximately 2 billion t/year of soil are transported down the Yellow River in China into the Yellow Sea (Lal and Stewart, 1990; McLaughlin, 1993; Zhang et al., 1997). The most costly off-site damages occur when soil particles enter lake and river systems (Lal and Stewart, 1990; Martin, 1997; Watershed, 2002). Of the billions of tons of soil lost from the United States and world cropland, nearly two-thirds finally is deposited in lakes and rivers (USDA, 1989; Pimentel, 1997). In some areas, heavy sedimentation leads to river and lake flooding (Myers, 1993). For example, some of the flooding that occurred in the midwestern United States during the summer of 1993 was caused by increased sediment deposition in the Mississippi and Missouri Rivers and their tributaries. These deposits raised the waterways, making them more prone to overflowing and flooding (Allen, 1994). Sediments disrupt and harm aquatic ecosystems by contaminating the water with soil particles and the fertilizer and pesticide chemicals they contain (Clark, 1987). Siltation of reservoirs and dams reduces water storage, increases the maintenance cost of dams, and shortens the lifetime of reservoirs (Pimentel et al., 1995).

Wind-eroded soil also causes off-site damage because soil particles propelled by strong winds act as abrasives and air pollutants (WEI, 2002; Wind Particles, 2002). Estimates are that soil particles sandblast U.S. automobiles and buildings, and cause about $8 billion in damages each year (Huszar and Piper, 1985; SCS, 1993; Pimentel et al., 1995). A prime example of the environmental impact of wind erosion occurs in the United States, where wind erosion rates average 13 t/ha/year and sometimes reach as much as 56 t/ha/year (Pimentel and Kounang, 1998; Ecology Action, 2002). Yearly off-site erosion costs in New Mexico, including health and property damage, are estimated to reach $465 million (Huszar and Piper, 1985). The off-site damage from wind erosion in the United States is estimated to cost nearly $10 billion each year (Pimentel et al., 1995).

The long range transport of dust by wind has implications for health worldwide. Griffin et al. (2001) report that about 20 human infectious disease organisms, like anthrax and tuberculosis, are easily carried in the soil particles transported by the wind.

Soil erosion contributes to global warming, because CO_2 is added to the atmosphere when the enormous amounts of biomass carbon in the soil are oxidized (Phillips et al., 1993; Lal et al., 1999; Lal, 2001, 2004; Walsh and Rowe, 2001). One hectare of soil may contain about 100 t of organic matter or biomass. The subsequent oxidation and release of CO_2 into the atmosphere, as the soil organic matter oxidizes, along with other atmospheric pollutants contributes to the global warming problem (Phillips et al., 1993; Lal, 2004). In fact, a feedback mechanism may exist wherein increased global warming intensifies rainfall which, in turn, increases erosion and continues the cycle (Lal, 2002).

CONSERVATION TECHNOLOGIES AND RESEARCH

Estimates are that agricultural land degradation alone can be expected to depress world food production approximately 30% during the next 25-year period (Buringh, 1989) or 50-year period (Kendall and Pimentel, 1994). These forecasts emphasize the need to implement known soil conservation techniques. These techniques include the use of biomass mulches, crop rotations, no-till, ridge-till, added grass strips, shelterbelts, contour row-crop planting, and various combinations of these. Basically all of these techniques require keeping the land protected from wind and rainfall energy by using some form of vegetative cover on the land (Troeh et al., 1991; Pimentel, 1993; Pimentel et al., 1995).

In the United States, during the past decade, soil erosion rates on croplands have been reduced nearly 25% using various soil conservation technologies (USDA, 1989, 1994, 2000a,b). Yet, even with this decline, soil is still being lost on croplands 10 times above its sustainability rate (USDA, 2000a,b). Unfortunately, soil erosion rates on rangelands have not declined during this same decade and remain at about six times sustainability (NAS, 2003).

Soil erosion is known to affect water runoff, soil water-holding capacity, soil organic matter, nutrients, soil depth, and soil biota. All of these influence soil productivity in both natural and managed ecosystems. Little is known about the ecology of the interactions of the various soil factors and their interdependency (Lal and Stewart, 1990; Pimentel, 1993). The effects of soil erosion on the productivity of both natural and managed ecosystems require serious research to develop effective soil and water conservation measures. Farmers will need incentives to fully implement conservation methods.

PRODUCTIVE SOILS AND FOOD SECURITY

There is no doubt that soil erosion is a critical environmental problem throughout the world's terrestrial ecosystems. Erosion is a slow insidious process. Indeed 1 mm of soil, easily lost in just one rain or wind storm, is so minute that its loss goes unnoticed. Yet this loss of soil over a hectare of cropland amounts to 15 t/ha. Replenishing

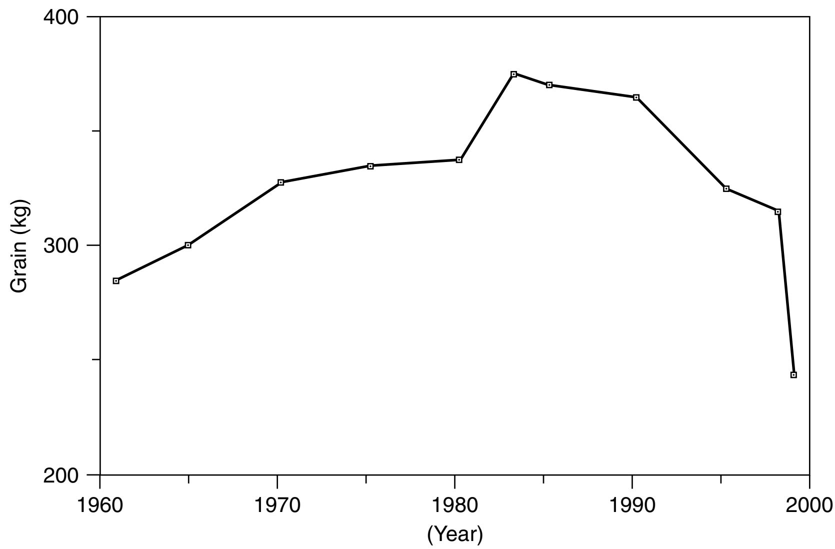

FIGURE 15.3 Cereal grain production per capita in the world from 1961 to 2000. (FAO, 1961–2000. *Quarterly Bulletin of Statistics*. 1–13.)

this amount of soil under agricultural conditions requires approximately 20 years, but meanwhile this soil is increasingly less able to support crop growth. Simultaneously, equally important losses of water, nutrients, soil organic matter, and soil biota are occurring. Forest, rangeland, and natural ecosystems are harmed when soil loss is ignored.

Concerning future food security, where cropland degradation is allowed to occur, crop productivity is significantly reduced. Shortages of cropland are already having negative impacts on world food production (Brown, 1997). For example, the Food and Agricultural Organization (FAO) of the United Nations reports that the availability of food per capita has been declining for nearly two decades, based on available cereal grains FAO (1961–2000) (Figure 15.3). Cereal grains make up 80%–90% of the world's food. Although grain yields per hectare in both developed and developing countries are still increasing, these increases are slowing while the world population continues to escalate. Now, and in the future decades, crop yields must be shared with more and more people (FAO, 1961–2000; PRB, 2002).

Worldwide, soil erosion continues unabated while the human population and its requirements for food, fiber, and other resources expand geometrically. Indeed, achieving future food security for all people depends on conserving fertile soil, water, energy, and biological resources. Careful management of all of these vital resources deserve high priority to ensure the effective protection of our agricultural and natural ecosystems. If conservation is ignored, the 3.7 billion malnourished people in the world will grow and per capita food production will decline further (WHO, 2004).

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