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Ecology of Soil Erosion in Ecosystems

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Abstract

Each year, about 75 billion tons of soil are eroded from the world's terrestrial ecosystems. Most agricultural land in the world is losing soil at rates ranging from 13 tons/ha/year to 40 tons/ha/year. Because soil is formed very slowly, this means that soil is being lost 13–40 times faster than the rate of renewal and sustainability. Rain and wind energy are the two prime causes of erosion from tilled or bare land. Erosion occurs when the soil lacks protective vegetative cover. Soil erosion reduces the productivity of the land by loss of water, soil organic matter, nutrients, biota, and depth of soil. The greatest threat to providing food for a rapidly growing human population is soil erosion. Abandoned, eroded agricultural land is replaced by clearing forested ecosystems.

Key words: soil; erosion; food; agriculture; nutrients; water.

Introduction

Soil erosion from land areas is widespread and adversely affects all natural and human-managed ecosystems, including agriculture and forestry. For that reason, soil erosion ranks as one of the most serious environmental problems in the world. Its effects are pervasive, and its damages are long lasting (Pimentel and others 1995a).

Although soil erosion has occurred throughout history, it has intensified as expanding human populations, coupled with their diverse activities, intrude farther into natural ecosystems. Erosion degrades soil quality in natural, agricultural, and forest ecosystems, thereby reducing the productivity of the land. As a result, the diversity of plants, animals, and microbes is diminished. Ultimately, the stability of entire ecosystems is threatened (Pimentel and others 1995a). To offset the damages that erosion inflicts on crops, large quantities of fertilizers and pesticides, plus irrigation, are intensively used. Not only are these inputs fossil-energy dependent, but they also harm human health and pollute the environment (Pimentel and others 1995a).

When agricultural land is eroded and can no longer be made productive, it is abandoned. To compensate for the loss, forests are cleared to provide needed agricultural land (Myers 1989). Indeed, erosion is the major cause of the deforestation now taking place throughout the world.

This article reviews the global dimensions of soil erosion and the impact erosion has on both natural and managed ecosystems.

Measuring Soil Erosion

Although soil erosion has been taking place slowly in natural ecosystems throughout geologic time, its cumulative impact over billions of years is significant. Worldwide, erosion rates range from a low of 0.001–2 tons/hectare/year (t/ha/yr) on relatively flat land with grass and/or forest cover to rates ranging from 1 to 5 t/ha/yr on mountainous regions with normal vegetative cover. Even low rates of erosion sustained over billions of years result in the displacement of soil. Often eroded soil accumulates in valleys, forming vast alluvial plains. Over a period of 100 years at an erosion rate of 2 t/ha/yr on 10 ha, erosion deposits soil equivalent to about 1 ha of land with a soil depth of 15 cm. The large deltas of the

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world, such as the Nile and the Mississippi, are the result of many centuries of erosion.

On sloping agricultural land under tropical rainfall, as much as 400 t/ha/yr of soil is lost (Pimentel unpublished report, 1990). Under arid conditions with relatively strong winds, as much as 5600 t/ha/yr of soil has been reported lost (Gupta and Raina 1996).

The large amounts of soil that are eroded from the land end up in streams, lakes, and other ecosystems. The US Department of Agriculture (USDA 1989) reports that 60% of the water-eroded soil ends up in streams. Further evidence that large amounts of water-eroded soil end up in streams and rivers is the fact that approximately 2 billion tons/year of soil are transported down the Yellow River in China into the gulf (Follett and Stewart 1985; Lal and Stewart 1990; McLaughlin 1993; Zhang and others 1997).

According to some investigators, approximately 75 billion tons of fertile soil are lost annually from the world's agricultural systems (Myers 1993), whereas other investigators have estimated that only 24 billion tons of soil are lost each year (Crosson 1997). In fact, the 75 billion tons is a conservative value. Soil scientists Lal and Stuart (1990) and Wen (1997) report that 6.6 billion tons of soil per year are lost in India and 5.5 billion tons are lost annually in China. Based on the fact that these two countries occupy about 13% of the world's total land area, the estimated 75 billion tons of soil lost per year worldwide is entirely logical. The amount of soil lost in the United States is more than 4 billion tons per year. In addition, serious soil erosion takes place in other regions of the world (Pimentel 1993; Oldeman 1997).

Causes of Erosion

Erosion occurs when soil is exposed to water or wind energy. Raindrops hit exposed soil with great energy and launch soil particles along with the water into the air. Raindrop splash and resulting sheet erosion remove a thin film of soil from the land surface. Sheet erosion is the dominant form of erosion (Allison 1973; Foster and others 1985). The impacts of both are intensified on sloping land, where more than half of the soil contained in the splashes is carried downhill to valleys and waterways (Pimentel and others 1995a).

Wind energy dislodges soil particles and carries them off the land. Airborne soil particles are often transported thousands of miles. For instance, soil particles eroded from African ecosystems have been identified as far west as Brazil and Florida (Simons 1992), whereas Chinese soil eroded during spring plowing has been found deposited in Hawaii (Parrington and others 1983).

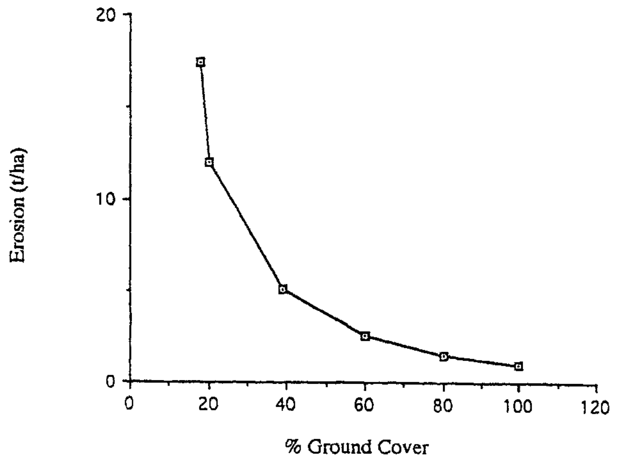

Figure 1. Soil erosion rates related to percentage of ground cover in Utah and Montana. After Trimbel and Mendel (1995).

Land areas covered by plant biomass, living or dead, are protected and experience reduced soil erosion because raindrop and wind energy is dissipated by the biomass layer. In Missouri, for example, barren land lost soil 123 times faster than did land covered with sod, which lost soil at less than 0.1 t/ha/yr (US Forest Service 1936). 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) (Figure 1).

Loss of vegetative cover is especially widespread in developing countries because population densities are high, agricultural practices frequently are inadequate, and cooking and heating often depend on the use of crop residues for fuel. For example, about 60% of crop residues in China and 90% in Bangladesh 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). Such practices leave the soil barren and fully exposed to rain and wind energy.

Erosion rates on sloping lands are exceedingly high. Erosion rates are high especially on marginal and steep lands that are being converted from forests to agricultural use to replace the already eroded, unproductive cropland (Lal and Stewart 1990). In Nigeria, for instance, cassava fields on steep slopes (approximately 12% slope) lost 221 t/ha/yr, compared with a loss of 3 t/ha/yr on relatively flat land (less than 1% slope) (Aina and others 1977). Similarly, 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 are as high as 400 t/ha/yr (Lal and Stewart 1990).

In forested areas, a minimum of 60% forest cover of the landscape is necessary to prevent soil erosion (Singh and Kaur 1989). The significance of this problem is illustrated in the Himalayan regions of India where the lower mountain areas are heavily forested. As the human population has increased there, extensive deforestation has followed. Now only 35% of that region is covered with forests and frequent landslides and soil erosion are common problems. Hawley and Dymond (1988) reported that 100% tree cover reduced storm damage and landslides at least 70%.

The structure of the soil itself 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. Typically, these soils have low infiltration rates and, therefore, are subject to high rates of water runoff with the eroded soil being carried away in the water flow (Foster and others 1985).

Although world agricultural production accounts for about three-quarters of the soil erosion worldwide, erosion also occurs in other human-modified ecosystems (El-Swaify and others 1985; Lal and Stewart 1990). The construction of roadways, 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/yr, erosion associated with construction is relatively brief, generally lasting only while the construction disturbs the land surface. Once the disturbed land surface is seeded to grass or vegetation regrows naturally, erosion decreases (International Erosion Control Association 1991).

Natural areas also suffer erosion; this is especially evident along stream banks. There erosion occurs naturally from the powerful action of moving water. On steep slopes (30% or more), a stream cut through adjacent land can cause significant loss of soil (Alonso and Combs 1989). Even on relatively flat land with a 2% slope, stream banks are eroded easily, especially during heavy rains and flooding. The presence of cattle in and around streams further increases stream-bank erosion. For example, in Wisconsin, a stream area inhabited by cattle lost about 60 tons of soil along each kilometer of stream length per year (Trimble 1994; Trimble and Mendel 1995).

As expected, erosion accompanies landslides and earthquakes (Bruijnzeel 1990). Overall, the erosion impact from earthquakes is comparatively minimal because these events are relatively rare worldwide. In contrast, for landslides—which are more frequent than earthquakes—the damage is more widespread. Landslides are usually associated with diverse human activities, such as the construction of roads and buildings and the removal of forests.

Soil Loss in Agricultural Lands

Cropland

Nearly one-half of the earth's land surface is devoted to agriculture; of this, about one-third is planted to crops and two-thirds to pasture land (USDA 1993). Of the two, cropland is more highly susceptible to erosion because it is tilled repeatedly. This practice exposes the soil to wind and water erosion. In addition, cropland often is left bare between plantings for several months of the year. Erosion on agricultural land is intense and estimated to be 75 times greater than that occurring in natural forest areas (Myers 1993).

On croplands, it is common to find that up to 100–200 t/ha/yr of soil have been eroded either by rainfall or wind or by a combination (Maass and Garcia-Oliva 1990). In extreme circumstances, erosion may exceed 450 t/ha/yr (Hurni 1985; Lal and Stewart 1990; Troeh and others 1991; Huang 1996).

Currently, about 80% of the world's agricultural land suffers moderate to severe erosion, while only 10% experiences relatively slight erosion (Pimentel 1993; Speth 1994; Lal 1994). Worldwide, erosion on cropland averages about 30 t/ha/yr and ranges from 0.5 to 400 t/ha/yr (Pimentel and others 1995a). As a result of erosion, during the last 40 years, about 30% of the world's arable land has become unproductive and, therefore, has been abandoned for agricultural use [World Resources Institute (WRI) 1994]. The nearly 1.5 billion ha of arable land that are now under cultivation for crop production are about equal in area to the amount of arable land (2 billion ha) that has been abandoned by humans since farming began (Lal 1990, 1994). The abandoned land, once biologically and economically productive, now produces little biomass and has lost most of its initial biodiversity of plants and animals (Pimentel and others 1992; Heywood 1995).

The lowest erosion rates on cropland average about 13 t/ha/yr and occur in the United States and Europe (Barrow 1991; USDA 1994). However, these relatively low rates of erosion greatly exceed the average rate of natural soil formation, which ranges from 0.5 to 1 t/ha/yr (Troeh and Thompson 1993; Lal 1994; Pimentel and others 1995a). More than 90% of US cropland now is losing soil faster than the sustainable, replacement rate (Hudson 1982; Lal 1984).

Even so, in the United States, erosion is severe in some of the most productive agricultural ecosystems. For instance, one-half of the fertile topsoil of Iowa has been lost during the last 150 years of farming because of erosion (Risser 1981; Klee 1991). Unfortunately, high rates of erosion (about 30 t/ha/yr) continue there because of the rolling hills 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. Intensive agriculture is employed in both of these regions and monocultural plantings are common. Also, in many areas, fields are left unplanted during the late fall and winter months, exposing the soil to erosion.

Worldwide, soil erosion rates are highest in agroecosystems located in Asia, Africa, and South America, averaging 30–40 t/ha/yr. In developing countries, soil erosion is particularly severe on small farms because they often occupy marginal lands where the soil quality is poor and the topography steep and hilly. In addition, the poor farmers raise row crops such as corn, which are highly susceptible to erosion (Southgate and Whitaker 1992). For example, in the Sierra region of Ecuador, 60% of the cropland was recently abandoned because erosion and inappropriate agricultural practices that left the land exposed to water and wind erosion caused severe soil degradation (Southgate and Whitaker 1992). Similar problems are evident in the Amazonian region of South America, especially where large forested areas are being cleared to provide more land for crops and livestock.

Pasture Land

In contrast to the average soil loss of 13 t/ha/yr from US cropland, pastures lose about 6 t/ha/yr (USDA 1994). However, erosion rates intensify whenever overgrazing occurs. This now is occurring on more than half of the world's pasture land (WRI 1994). In many developing countries, heavy grazing by sheep and goats has removed most of the vegetative cover, exposing the soil to erosion. Even in the United States, about 54% of the pasture lands, including those on federal lands, is now overgrazed and has become subject to high erosion rates (Hood and Morgan 1972; Byington 1986).

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/yr (Bennett 1939; Roose 1988; Lal 1994). Tree leaves and branches intercept and diminish rain and wind energy, while the leaves and branches cover the soil under the trees to protect the soil further. However, this changes dramatically when forests are cleared for crop production or pasture. 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 erodibility of the soils, their limited fertility, and overall poor soil type (Southgate and Whitaker 1992).

Effects of Erosion on Productivity

Erosion reduces the overall productivity of terrestrial ecosystems in several ways. First, in order of importance, erosion increases water runoff, thereby decreasing water infiltration and the water-storage capacity of the soil (Troeh and others 1991; Pimentel and others 1995a). Also, organic matter and essential plant nutrients are lost in the erosion process and soil depth is reduced. These changes reduce biodiversity in the soil (Troeh and others 1991; Pimentel and others 1995a). Because 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. This diminishes nutrient levels in the soil and also reduces the natural biota biomass and the biodiversity of the entire ecosystem.

Overall, the cumulative effects of erosion directly diminish plant productivity. For example, erosion reduced corn productivity by 12%–21% in Kentucky, 0–24% in Illinois and Indiana, 25%–65% in the southern Piedmont of Georgia, and 21% in Michigan (Frye and others 1982; Olson and Nizeyimana 1988; Mokma and Sietz 1992). In the Philippines over the past 15 years, erosion caused declines in corn production by as much as 80% (Dregne 1992). Such major reductions in food-crop yields are particularly serious at a time in history when the growing human population continues to require increased quantities of food and more than 2 billion people in the world are malnourished (World Health Organization 1995; Pimentel and others 1997a).

Water

Water is a prime limiting factor for productivity in all terrestrial ecosystems because all vegetation requires enormous quantities of water for its growth and for the production of fruit (NSESPRPC 1981; Follett and Stewart 1985; Falkenmark 1989). For example, a hectare of corn or wheat will transpire more than 4 million L of water each growing season (Leyton 1983) and lose an additional 2 million L of water by evaporation from the soil (Waldren 1983; Donahue and others 1990).

Table 1. Water and Soil Loss Related to Various Conservation Technologies That Reduce Water Runoff and Soil Erosion

		% Reduced		
Treatments	Location	Runoff	Soil Erosion	References
4 t/ha mulch/No mulch	India	58	72	Kukal and others 1993
Contour cultivation/No contour cultivation	India	—	54	Kukal and others 1993
Wheat–oat–barley–hay–hay/Wheat–fallow	Canada	—	89	Monreal and others 1995
No grazing pasture/Very heavy grazing	Ethiopia	330	330	Mwendera and Saleem 1997
No till + cover crop/Conventional till	Brazil	400	130	Busscher and others 1996
Cover crop–corn/Conventional	USA	15	110	Martin and Cassel 1992
Cover crop–silage corn/Conventional silage corn	USA	—	244	Reeves 1994
No till cotton/Conventional cotton	USA	140	900	Langdale and others 1994
Alley cropping corn[a]/Conventional	Philippines	75	99	Comia and others 1994

[a]*Alley cropping corn with leguminous tree on 17% slope.*

When erosion occurs, the amount of water runoff significantly increases, and with less water entering the soil, less is available to support the growing vegetation (Table 1). Moderately eroded soils absorb 10–300 mm less water per hectare per year from rainfall than uneroded soils. This represents a decrease of 7%–44% in the amount of water available to the vegetation (Wendt and Burwell 1985; Wendt and others 1986; Murphee and McGregor 1991). A diminished absorption rate of 20%–30% of rainfall represents significant water shortages for all vegetation, including crops (Elwell 1985). Lal (1976) reported that erosion has reduced water infiltration in some tropical soils by up to 93%.

In general, when water availability for the agricultural ecosystem is reduced from 20% to 40% in the soil, plant productivity is reduced from 10% to 25%, depending also on total rainfall, soil type, slope, and other factors. Such major reductions in plant biomass also reduce the soil biota and the overall biodiversity within the ecosystem (Heywood 1995).

Nutrients

When soil is eroded, basic plant nutrients such as nitrogen, phosphorus, potassium, and calcium also are lost. Eroded soil typically contains about three times more nutrients than the soil left behind on the eroded land (Lal 1980; Young 1989). A ton of fertile topsoil typically contains 1–6 kg of nitrogen, 1–3 kg of phosphorus, and 2–30 kg of potassium, whereas soil on eroded land frequently has nitrogen levels of only 0.1–0.5 kg/t (Alexander 1977; Troeh and others 1991). Plant productivity is significantly reduced when soil nutrient levels are this low.

If the soil is relatively deep, such as 300 mm, and 10–20 tons of soil is lost per hectare, the nutrients lost in the erosded soil can be replaced with the application of commercial fertilizers and/or livestock manure (Pimentel and others 1995a). However, the loss of nutrients can be expensive for the farmer and nation. For instance, Troeh and colleagues (1991) estimate that the United States loses $20 billion annually in nutrients because of soil erosion.

Soil Organic Matter

Both wind and water erosion selectively remove the fine organic particles in the soil, leaving behind large particles and stones. Fertile soils frequently contain about 100 tons of organic matter per hectare (or 4% of the total soil weight) (Follett and others 1987; Young 1990). Because most of the organic matter is close to the soil surface in the form of decaying leaves and stems, erosion of the topsoil significantly decreases soil organic matter. Several studies have demonstrated that the soil removed by either wind or water erosion is 1.3–5.0 times richer in organic matter than the soil left behind (Barrows and Kilmer 1963; Allison 1973).

Soil organic matter facilitates the formation of soil aggregates and increases soil porosity. In this way, it improves soil structure, which in turn facilitates water infiltration and ultimately the overall productivity of the soil (Chaney and Swift 1984; Langdale and others 1992). In addition, organic matter aids cation exchange, enhances root growth, and stimulates the increase of important soil biota (Allison 1973). About 95% of the soil nitrogen and 25%–50% of the phosphorus are contained in the organic matter (Allison 1973).

Once the organic matter layer is depleted, the productivity of the ecosystem, as measured by crop-plant yields, declines both because of the degraded soil structure and the depletion of nutrients contained in the organic matter. For example, the reduction of soil organic matter from 1.4% to 0.9% lowered the yield potential for grain by 50% (Libert 1995).

When nutrient resources are depleted by erosion, plant growth is stunted and overall productivity declines (Pimentel and others 1995a). Soils that suffer severe erosion may produce 15%–30% lower crop yields than uneroded soils (Olson and Nizeyimana 1988; Schertz and others 1989; Follett and Stewart 1985; Langdale and others 1992). In addition to low yields, the total biomass of the biota and overall biodiversity of these ecosystems are substantially reduced (Heywood 1995).

Soil Depth

As plants grow, they need soils of adequate depth in which to extend their roots. Various soil biota also require a specific soil depth (Pimentel and others 1995a). Thus, when soil depth is substantially reduced by erosion from 30 cm to less than 1 cm, plant root space is minimal and, concurrently, valuable soil biota nearly disappear.

Biomass and Biodiversity

The biological diversity existing in any natural ecosystem is directly related to the amount of living and nonliving organic matter present in the ecosystem (Wright 1983, 1990). By diminishing soil organic matter and overall soil quality, erosion reduces biomass productivity in ecosystems. Ultimately, this has a profound effect on the diversity of plants, animals, microbes, and other forms of life present in the ecosystem.

Numerous positive correlations between biomass and species abundance have been established (Elton 1927; Odum 1978; Sugden and Rands 1990; M. Giampietro personal communication, 1997, Insituto Nazionale della Nutrizione, Rome, Italy). Vegetation is the main component of ecosystem biomass and provides the resources needed by animals and microbes. This relationship is summarized in Table 2.

Plants, animals, and microbes are a vital component of the soil, as mentioned, and constitute a large measure of the soil biomass. One square meter of soil may support about 200,000 arthropods and enchytraeids and billions of microbes (Wood 1989; Lee and Foster 1991). A hectare of productive soil may have a microbial and invertabrate biomass weighing nearly 10,000 kg/ha (Table 2). Anderson (1978) reported that a favorable temperate-forest soil with abundant organic matter supports up to 1000 species of animals per square meter, including arthropods, nematodes, and protozoa. Soil bacteria and fungi add another 4000–5000 species to the biodiversity in moist, organic forest soils (Heywood 1995).

Table 2. Biomass of Various Organisms per Hectare in a New York State Pasture[a]

Organism	Biomass (kg fresh weight)
Plants	20,000
Fungi	4000
Bacteria	3000
Annelids	1320
Arthropods	1000
Protozoa	380
Algae	200
Nematodes	120
Mammals	1.2
Birds	0.3

[a] *After Pimentel and colleagues (1992).*

Erosion rates that are 10–20 times higher than the sustainability rate (less than 0.5 to 1 t/ha/yr) decrease the diversity and abundance of soil organisms (Atlavinyte 1964, 1965), whereas agricultural practices that maintain adequate soil organic matter content favor the proliferation of soil biota (Reid 1985). For example, the simple practice of adding straw mulch on the soil surface increased soil organic matter and the number of living organisms as much as threefold (Teotia and others 1950). Similarly, the application of organic matter or manure enhanced earthworm and microorganism biomass as much as fivefold (Ricou 1979). In the former USSR, species diversity of macrofauna (mostly arthropods) increased 16% when organic manure was added to experimental wheat plots (Bohac and Pokarzhevsky 1987). Macrofauna (mostly arthropods) species diversity more than doubled when organic manure was added to grassland plots in Japan (Kitazawa and Kitazawa 1980).

Arthropod biomass increased significantly when soil organic matter was added to the agriculture. For example, the biomass of arthropods increased from twofold to sevenfold per hectare when organic matter in manure was added to wheat and mangold crops in the United Kingdom (Morris 1922; Raw 1967). Also, when organic manure was added to agricultural land in Hungary, soil microbial biomass increased tenfold (Olah-Zsupos and Helmeczi 1987). Because increased biomass generally is correlated with increased biodiversity, it is logical to assume that the increase in biomass of arthropods and microbes represents an increase in biodiversity (Pimentel and others 1992).

The relationship between biomass and biodiversity was further illustrated in field experiments with collards in which arthropod species diversity rose fourfold in the experimental plots that had the highest collard biomass compared with control collard plots (Pimentel and Warneke 1989). Ward and Lakhani (1977) reported that the number of arthropod species associated with an ecosystem containing juniper bushes increased fourfold when the number of bushes was increased 100-fold. Elsewhere, a strong correlation between plant biomass productivity and bird species diversity was reported when a 100-fold increase in plant biomass productivity yielded a tenfold increase in bird diversity (Wright 1983, 1990).

Indirect effects of erosion on ecosystems frequently may be nearly as damaging as the direct effects of reducing plant productivity. For example, the stability and biodiversity of grasslands were significantly reduced when plant species reduction occurred (Tilman and Downing 1994). As the number of plant species decreased from 25 species to five or fewer, the grassland became less resistant to drought and the total amount of biomass declined more than fourfold. As a result the grassland was more susceptible to drought conditions and recovery of productivity required more time than in the species-rich state.

The effects of erosion may be responsible for the loss of a keystone species, an absence that may have a cascading effect on a wide array of species within the ecosystem. Species that act as keystone species include plant types that maintain the productivity and integrity of the ecosystem; predators and parasites that control the feeding pressure of some organisms on vital plants; pollinators of various vital plants in the ecosystem; seed dispersers; and the plants and animals that provide a habitat required by other essential species, like biological nitrogen fixers (Heywood 1995; Daily 1996). Hence, the regular activities within an ecosystem may be interrupted or even eliminated. The impacts of this can be particularly severe especially in agroecosystems when, for instance, pollinators are drastically reduced and/or eliminated.

Soil biota perform many beneficial activities that improve soil quality and productivity. For example, soil biota recycle basic nutrients required by plants for their growth (Van Rhee 1965; Pimentel and others 1980, 1997b). In addition, the tunneling and burrowing activities of earthworms and other soil biota enhance productivity by increasing water infiltration into the soil. Earthworms, for instance, may produce up to 220 tunnel openings per square meter (3–5 mm in diameter). These channels enable water to run rapidly into the soil, thereby increasing infiltration rates (Anderson 1988).

Other soil biota contribute to soil formation and productivity by mixing soil components, enhancing aggregate stability, and preventing soil crusting. Earthworms bring between 10 and 500 t/ha/yr of soil from underground to the soil surface (Edwards 1981; Lavelle 1983; Lee 1985), while insects bring a smaller amount to the surface (Hole 1981; Zacharias and Grube 1984; Lockaby and Adams 1985). This churning and mixing of the upper soil redistributes nutrients, aerates the soil, exposes matter to the climate for soil formation, and increases infiltration rates, thus making conditions favorable for increased soil formation and plant productivity. 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 and others 1995). This snail activity helps form about 1000 kg of soil per hectare per year, which is equal to the annual soil formation by windborne deposits.

Controlling erosion not only conserves the quality of soils but enhances vegetative growth and increases total biodiversity.

Sediments and Wind-Blown Soil Particles

Beyond its direct effect on agricultural and forest ecosystems, the impact of erosion reaches far into the surrounding environment. Major off-site problems include earth-dam failures, eutrophication of waterways, siltation of harbors and channels, loss of reservoir storage, loss of wildlife habitat, disruption of stream ecology, and flooding of land and communities, plus increased costs for water treatment (Gray and Leiser 1989).

The most costly off-site damages occur when soil particles enter water systems (Lal and Stewart 1990). Of the billions of tons of soil lost from US and world cropland, nearly two-thirds finally are deposited in streams and rivers (USDA 1989; Pimentel 1997). These sediments 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 and others 1995a).

Furthermore, heavy sedimentation frequently 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 original depth of the waterways, making them more prone to overflowing and flooding the surrounding area (Allen 1994).

Wind-eroded soil is responsible for off-site damage because soil particles propelled by strong winds act as abrasives and air pollutants. Estimates are that soil particles sandblast US automobiles and buildings and cause about $8 billion in damages each year (Huszar and Piper 1985; Soil Conservation Service 1993; Pimentel and others 1995a). A prime example of the environmental impact of wind erosion occurs in New Mexico, where about two-thirds of the land is used for agriculture, including grazing, and erosion rates on pastures often exceed 6 t/ha/yr and sometimes reach as much as 100 t/ha/yr. Yearly off-site erosion costs in New Mexico, including health and property damage, are estimated as high as $465 million (Huszar and Piper 1985). Assuming similar costs for other states, the off-site damages from wind erosion alone could cost nearly $10 billion each year (Pimentel and others 1995a).

Soil erosion also contributes to the global warming problem by adding carbon dioxide to the atmosphere as enormous amounts of biomass carbon in the soil are oxidized (Phillips and others 1993). As mentioned, a hectare of soil may contain about 100 tons of organic matter or biomass. When the forces of erosion uncover the carbon from this organic matter, it is exposed and oxidizes. The subsequent release of carbon dioxide into the atmosphere contributes to the global warming problem (Phillips and others 1993). In fact, a feedback mechanism may exist wherein increased global warming intensifies rainfall, which, in turn, increases erosion and continues the cycle (Lal 1990).

Conservation Technologies and Research

Erosion adversely affects crop productivity by reducing water availability, the water-holding capacity of the soil, nutrient levels, soil organic matter, and soil depth (Pimentel and others 1995a). Estimates are that agricultural land degradation alone is expected to depress world food production between 15% and 30% during the next 25-year period (Buringh 1989), emphasizing the need to implement known soil conservation techniques, including biomass mulches, no till, ridge till, grass strips, shelterbelts, terracing, contour planting, crop rotations, and combinations of these. All of these techniques basically require keeping the land protected from wind and rainfall effects by some form of vegetative cover (Pimentel and others 1995a).

In the United States during the past decade, soil erosion rates on croplands have decreased nearly 25% using various soil conservation technologies (USDA 1989, 1994). Even with this decline, soil is still being lost on croplands at a rate 13-times greater than the sustainability rate (Pimentel and others 1995b). Although soil erosion has declined on croplands, soil erosion rates on pastures and rangelands have not declined during this same period (USDA 1989, 1994).

Soil erosion is known to affect water runoff, soil water-holding capacity, soil organic matter, nutrients, soil depth, and soil biota, and all of these factors influence soil productivity in natural and managed ecosystems. Little is known about the ecology of the interactions of these various soil factors and their interdependency (Lal and Stewart 1990; Pimentel 1993). In addition, more information is needed on the effects of soil erosion on the productivity of natural and managed ecosystems.

Conclusion

Soil erosion is a critical environmental problem throughout the world's terrestrial ecosystems. Erosion is a slow insidious process. One millimeter of soil, easily lost in one rainstorm or windstorm, is seemingly so minute that its loss goes unnoticed. Yet this loss of soil over a hectare of cropland amounts to 15 tons. Reforming that amount of soil under natural circumstances requires 20 years.

Erosion inflicts multiple, serious damages in managed ecosystems like crops, pastures, or forests—as well as in natural ecosystems. In particular, erosion reduces the water-holding capacity because of rapid water runoff, and reduces soil organic matter. As a result, nutrients and valuable soil biota are reduced. Separately or together, these factors diminish the productivity of all vegetation and animals in ecosystems. At the same time, species diversity of plants, animals, and microbes is significantly reduced.

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 soil, water, energy, and biological resources. Conservation of these vital resources must receive high priority to ensure the effective protection of managed and natural ecosystems. If it is ignored, the quality of life for all humans will suffer.

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