Environmental and Economic Costs of Soil Erosion and Conservation Benefits

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Soil erosion is a major environmental threat to the sustainability and productive capacity of agriculture. During the last 40 years, nearly one-third of the world's arable land has been lost by erosion and continues to be lost at a rate of more than 10 million hectares per year. With the addition of a quarter of a million people each day, the world population's food demand is increasing at a time when per capita food productivity is beginning to decline.

Soil erosion is a major environmental and agricultural problem worldwide. Although erosion has occurred throughout the history of agriculture, it has intensified in recent years (*1*). Each year, 75 billion metric tons of soil are removed from the land by wind and water erosion, with most coming from agricultural land (*2*). The loss of soil degrades arable land and eventually renders it unproductive. Worldwide, about 12×10^6 ha of arable land are destroyed and abandoned annually because of nonsustainable farming practices (*1*), and only about 1.5×10^9 ha of land are being cultivated (*3, 4*). Per capita shortages of arable land exist in Africa, Asia, and Europe because of lost eroded land and the expansion of the world population to nearly 6 billion (*1, 5*).

To adequately feed people a diverse diet, about 0.5 ha of arable land per capita is needed (*6*), yet only 0.27 ha per capita is available. In 40 years, only 0.14 ha per capita will be available both because of loss of land and rapid population growth (*5*). In many regions, limited land is a major cause of food shortages and undernutrition (*4, 7*). Over 1 billion humans (about 20% of the population) now are malnourished because of food shortages and inadequate distribution (*8, 9*). With the world population increasing at a quarter of a million per day and continued land degradation by erosion, food shortages and malnutrition have the potential to intensify (*10, 11*).

The use of large amounts of fertilizers, pesticides, and irrigation help offset deleterious effects of erosion but have the potential to create pollution and health problems, destroy natural habitats, and contribute to high energy consumption and unsustainable agricultural systems. Erosion also is a major cause of deforestation: As agricultural land is degraded and abandoned, more forests are cut and converted for needed agricultural production (*12*).

In this article, we (i) examine the ways in which erosion reduces soil fertility and crop productivity, (ii) assess the environmental and economic costs of soil erosion, and (iii) compare various agricultural techniques and practices that reduce erosion and help conserve water and soil resources.

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Erosion on Croplands and Pastures

Worldwide erosion rates. Of the world's agricultural land, about one-third is devoted to crops and the remaining two-thirds is devoted to pastures for livestock grazing (*4, 13*). About 80% of the world's agricultural land suffers moderate to severe erosion, and 10% suffers slight to moderate erosion (*9*). Croplands are the most susceptible to erosion because their soil is repeatedly tilled and left without a protective cover of vegetation. However, soil erosion rates may exceed 100 tons ha^{-1} $year^{-1}$ in severely overgrazed pastures (*14*). More than half of the world's pasturelands are overgrazed and subject to erosive degradation (*15*).

Soil erosion rates are highest in Asia, Africa, and South America, averaging 30 to 40 tons ha^{-1} $year^{-1}$, and lowest in the United States and Europe, averaging about 17 tons ha^{-1} $year^{-1}$ (*16*). The relatively low rates in the United States and Europe, however, greatly exceed the average rate of soil formation of about 1 ton ha^{-1} $year^{-1}$ (the rate of conversion of parent material into soil in the A, E, and B horizons) (*17*). Erosion rates in undisturbed forests range from only 0.004 to 0.05 ton ha^{-1} $year^{-1}$ (*18, 19*).

Erosion rates in the United States. In the last 200 years of U.S. farming, an estimated 10^8 ha (~30%) of farmland has been abandoned because of erosion, salinization, and waterlogging (*13, 18, 20*). Wind erosion appears to be worsening, while water erosion appears to be declining (*13, 21, 22*).

Croplands in the United States lose soil at an average rate of 17 tons ha^{-1} $year^{-1}$ from combined water and wind erosion, and pastures lose 6 tons ha^{-1} $year^{-1}$ (*13*). About 90% of U.S. cropland is losing soil above the sustainable rate (*23, 24*). About 54% of U.S. pastureland (including federal lands) is overgrazed and subject to high rates of erosion (*25, 26*).

The extent of U.S. soil erosion is well documented. One-half of the fertile topsoil of Iowa has been lost during the last 150 years of farming (*27, 28*), and loss of topsoil continues at a rate of about 30 tons ha^{-1} $year^{-1}$ (*13*). Similarly, about 40% of the rich Palouse soils of the northwest United States has been lost in the past century.

During the past 50 years, the average farm size has more than doubled from 90 to 190 ha (*29, 30*). To create larger farms and fields, farmers have removed the grass strips, shelterbelts, and hedgerows that once protected soil from erosion (*23, 24, 31*). Crop specialization has also led to the use of heavier machines that damage the entire soil ecosystem (*32, 33*).

Erosion Processes

Erosion results from energy transmitted from rainfall and wind. Raindrops hit exposed soil with an explosive effect, launching soil particles into the air. In most areas, raindrop splash and sheet erosion are the dominant forms of erosion (*34, 35*). Erosion is intensified on sloping land, where more than half of the soil contained in the splashes is carried downhill.

Airborne soil particulates can be transported thousands of miles. For instance, soil particles from eroded African lands are blown as far as Brazil and Florida (*36*), and Chinese soil has been detected in Hawaii (*37*).

Factors Influencing Erosion

Erosion increases dramatically on steep cropland. Yet, steep slopes are now routinely being converted from forests for agricultural use because of the increasing needs of the human population and land degradation (*1*). Once under conventional cultivation, these steep slopes suffer high erosion rates: In Nigeria, cassava fields on steep (~12%) slopes lost 221 tons ha^{-1} $year^{-1}$, compared with an annual soil loss of 3 tons ha^{-1} $year^{-1}$ on flat (<1%) land (*38*). The Philippines, where over 58% of the land has slopes greater than 11%, and Jamaica, where 52% of the land has slopes greater than 20%, exhibit soil losses as high as 400 tons ha^{-1} $year^{-1}$ (*1*).

Living and dead plant biomass left on fields reduce soil erosion and water runoff by intercepting and dissipating raindrop and wind energy. In Missouri, for example, barren land lost soil at a rate 123 times that of land that was covered with sod (which lost <0.1 ton ha^{-1} $year^{-1}$) (*39*). Similarly in Oklahoma, areas without rye grass or wheat cover lost 2.5 to 4.8 times as much water as land with cover (*40*).

Loss of vegetative cover is particularly widespread in many third-world countries. About 60% of crop residues in China and 90% in Bangladesh are removed and burned for fuel each year (*41*). In areas where fuel is scarce, even the roots of grasses and shrubs are collected (*42*).

Both the texture and the structure of soil influence its susceptibility to erosion. Soils with medium to fine texture, low organic matter content, and weak structural development have low infiltration rates and experience increased water runoff (*35*).

Erosion and Productivity

Because of erosion-associated loss of productivity and population growth, the per capita food supply has been reduced over the past 10 years and continues to fall (*43*). The Food and Agriculture Organization reports that the per capita production of grains, which make up 80% of the world food supply, has been declining since 1984 (*44*).

Crop yields on severely eroded soil are lower than those on protected soils because erosion reduces soil fertility and water availability. Corn yields on some severely eroded soils have been reduced by 12 to 21% in Kentucky, 0 to 24% in Illinois and Indiana, 25 to 65% in the southern Piedmont (Georgia), and 21% in Michigan (*45–47*). In several areas of the Philippines, erosion has caused declines in corn productivity as severe as 80% over the last 15 years (*48*).

Erosion by water and wind adversely affects soil quality and productivity by reducing infiltration rates, water-holding capacity, nutrients, organic matter, soil biota, and soil depth (*33, 49, 50*). Each of these factors influences soil productivity individually but also interacts with the other factors, making assessment of the impacts of soil erosion on productivity difficult.

All crops require enormous quantities of water for their growth and the production of fruit (*51–53*). For example, during a single growing season, a hectare of corn (yield, 7000 kg ha^{-1}) transpires about 4×10^6 liters of water (*54*), and an additional 2×10^6 liters ha^{-1} concurrently evaporate from the soil (*55, 56*).

When erosion occurs, the amount of water runoff increases, so that less water enters the soil matrix and becomes available for the crop (Table 1). Moderately eroded soils absorb from 10 to 300 mm less water per hectare per year than uneroded soils, or between 7 to 44% of total rainfall (*57–60*). This degree of water loss reduces crop productivity; even a runoff rate of 20 to 30% of total rainfall can result in significant water shortages for crops (*61*). In the tropics, Lal (*31*) reported that erosion may reduce infiltration by up to 93%.

In addition to creating water deficiencies, soil erosion causes shortages of basic plant nutrients, such as nitrogen, phosphorus, potassium, and calcium, which are essential for crop production. A ton of fertile agricultural topsoil typically contains 1 to 6 kg of nitrogen, 1 to 3 kg of phosphorus, and 2 to 30 kg of potassium, whereas a severely eroded soil may have nitrogen levels of only 0.1 to 0.5 kg per ton (*50, 62*). Wind and water erosion selectively remove the fine organic particles, leaving behind large particles and stones. Eroded soil typically contains about three times more nutrients than the soil left behind (*63–65*).

When nutrient reserves are depleted by erosion, plant growth is stunted and crop yields decline (Table 2). Soils that suffer severe erosion may produce 15 to 30% lower corn yields than uneroded soils (*46, 52*), and with fertilization, the yield reductions range from 13 to 19% (*45–47*). Under the current average soil erosion rates (17 tons ha^{-1} $year^{-1}$), the loss of nitrogen, phosphorus, and potassium can be expected to cause a long-term drop in crop yields. If soil erosion is 1 ton ha^{-1} $year^{-1}$ or less, if crop residues are left on the land, and if nutrients are added to offset any of the nutrients removed with the crop, then soil quality and productivity will remain high and sustainable.

Organic matter, a necessary component of soil, facilitates the formation of soil aggregates, increases soil porosity, and thereby improves soil structure, water infiltration, and ultimately overall productivity (*66, 67*). In addition, organic matter increases water infiltration, facilitates cation exchange, enhances root growth, and stimulates the proliferation of important soil biota (*34*). About 95% of the nitrogen and 25 to 50% of the phosphorus is contained in organic matter (*34*).

Fertile topsoils typically contain about 100 tons of organic matter (or 4% of total soil weight) per hectare (*68, 69*). Because most of the organic matter is near the soil surface in the form of decaying leaves and stems, erosion of topsoil results in a rapid decrease in levels of soil organic matter. Several studies have demonstrated that the soil removed by either wind or water erosion is 1.3 to 5 times richer in organic matter than the soil left behind (*34, 70*). The loss of 17 tons of soil per hectare by rainfall removes nearly 2 tons of organic matter (*69*).

Once the organic matter layer is depleted, soil productivity and crop yields decline because of the degraded soil structure and depletion of nutrients. For example, the reduction of soil organic matter from 4.3 to 1.7% lowered the yield potential for corn by 25% in Michigan (*71*).

Although soil biota are often ignored in assessments of the impact of erosion, they are a critical component of the soil and constitute a large portion of the soil biomass. One square meter of soil may support populations of about 200,000 arthropods and enchytraeids and billions of microbes (*72, 73*). A hectare of good quality soil contains an average of 1000 kg of earthworms, 1000 kg of arthropods, 150 kg of protozoa, 150 kg of algae, 1700 kg of bacteria, and 2700 kg of fungi (*74*). Soil biota

Table 1. Water runoff rates compared for conservation versus conventional plantings of corn.

Treatment	Water runoff (cm depth)	Conserved water (cm)	Increased yield* (tons ha^{-1})
Corn stover mulch vs. no stover residue (*110*)	0.06 1.30	1.24	0.34
Rye cover mulch vs. residue burned (*111*)	3.9 17.4	13.5	3.4
Manure mulch vs. no manure (*112*)	9.0 13.1	4.1	1.1
Corn-oats-hay-hay vs. conventional continuous (*113*)	0.58 3.08	2.50	0.6
No-till in sod vs. conventional (*114*)	3.7 10.7	7.0	1.8
Level terraced vs. contour planted (*115*)	0.94 8.14	7.2	1.8
Dense planting vs. bare soil (*116*)	2.49 3.32	0.97	0.2
Reduced till vs. conventional (*117*)	2.1 3.6	1.5	0.4

*Increased yield based on the results of Troeh *et al.* (*50*).

recycle the basic nutrients required by plants (*74, 75*). Also, the tunneling and burrowing activities of earthworms and other soil biota enhance productivity by increasing water infiltration rates.

The erosion typical of conventional agriculture may decrease the diversity and abundance of soil organisms (*76, 77*), whereas practices that maintain the soil organic matter content at optimum levels favor the proliferation of soil biota (*78*). Thus, the simple practice of straw-mulching may increase biota threefold (*79*), and the application of organic matter or manure may increase earthworm and microorganism biomass as much as fivefold (*80*).

Soils form slowly: It takes between 200 and 1000 years to form 2.5 cm (1 inch) of topsoil under cropland conditions, and even longer under pasture and forest conditions (*24, 33, 61, 81*). In the United States, where 2.5 cm of soil are lost every 16.5 years, soil has been lost at about 17 times the rate at which it has formed (*17*). Estimates are that the average U.S. topsoil depth was about 23 cm in 1776. Today, after about 200 years of farming, the average depth has declined to about two-thirds of the original soil depth (~15 cm) (*82*).

Model of Erosion Effects on Crop Productivity

To assess how and to what extent erosion decreases crop productivity, it is necessary to consider the multiple factors that influence erosion rates, as well as the soil components that affect productivity. We have developed empirical models that incorporate the numerous factors affecting both erosion rates and soil productivity. The slope of the land, soil composition, and extent of vegetative cover influence the rate of erosion, and the soil depth, presence of soil biota, organic matter, water-holding capacity, and nutrient levels influence the soil's productive capacity. These factors form a complex and interdependent system. Changes in one factor subsequently affect all or many others. The models demonstrate how soil erosion causes the loss of soil nutrients, depth, biota, organic matter, and water resources and how these losses translate into reduced crop productivity. The models are based on the following set of assumptions: ~700 mm of rainfall, soil depth of 15 cm, slope of 5%, loamy soil, 4% organic matter, and soil erosion rate of 17 tons ha^{-1} $year^{-1}$. The models provide a perspective on the interdependence of the various factors associated with the ecological effects of erosion.

On the basis of empirical evidence, it appears that when soil erosion by water and wind occurs at a rate of 17 tons ha^{-1} $year^{-1}$, an average of 75 mm of water, 2 tons of organic matter, and 15 kg of available nitrogen are lost from each hectare each year (Table 3). In addition, soil depth is reduced by 1.4 mm, the water-holding capacity is decreased by less than 0.1 mm, and soil biota populations are diminished. When combined, these losses translate into an 8% reduction in crop productivity over the short term (1 year). The loss of water and nutrients account for nearly 90% of the loss in productivity (Table 3). This model assumes that the nutrients and water are not replaced.

Evaluated over the long term (20 years), empirical evidence again confirms that water and nutrient loss continue to have the greatest effect on crop productivity, accounting for 50 to 75% of the reduced productivity (*65*) (Table 2). A reduction in soil depth of 2.8 cm results in a reduction in productivity of about 7%. Soil depth is particularly critical because it takes hundreds of years to replace a single centimeter of lost topsoil. The other factors, including soil biota, water-holding capacity, and soil depth, become significant in the long term. Again, this model assumes that the lost nutrients and water are not replaced; if they were replaced, then the 20% loss estimate would be reduced by one-fourth to one-third (*45–47*). On a yearly basis, the effects of soil erosion often can be temporarily offset by the extensive use of fertilizers, irrigation, plant breeding, and other inputs. However, the long-term cumulative loss of

Table 2. Estimated annual economic and energetic costs (per hectare) of soil and water loss from conventional corn assuming a water and wind erosion rate of 17 tons ha^{-1} $year^{-1}$ over the long term (20 years).

Factors	Annual quantities lost	Cost of replacement (dollars)	Energetic costs (10^3 kcal)	Yield loss after 20 years of erosion (%)
Water runoff	75 mm*	30†	700‡	7*
Nitrogen	50 kg§		500‖	
Phosphorus	2 kg§	100§	3‖	8¶
Potassium	410 kg§		260‖	
Soil depth	1.4 mm*	16#	–	7**
Organic matter	2 tons*	–	–	4††
Water holding capacity	0.1 mm*	–	–	2‡‡
Soil biota	–	–	–	1§§
Total on-site		146	1460	20‖‖
Total off-site		50¶¶	100	
Grand total		196#	1560	

*Table 3. †The cost of replacing this much water by ground-water irrigation based on 1992 dollars (*118*). The value is reduced by 40% because it is assumed that water erosion accounts for 60% of U.S. erosion (*119*). However, if rainfall were abundant, then this replacement cost would not be necessary. ‡Energy required to pump ground water from a depth of 30 m (*120*). §Total nutrients loss, based on the results of Troeh *et al.* (*50*). ‖Energy required to replace the fertilizers lost (*121*). ¶Based on the total loss of 340 tons ha^{-1} of soil over 20 years and the mineralization and availability of the nutrients in this soil. #Estimated. **Based on reduced productivity of about 6% per loss of 2.5 cm of soil (*122*). ††Organic matter content of the soil was assumed to decline from 4 to 3% over this period, resulting in a 4% decline in productivity. ‡‡After the loss of 17 tons ha^{-1} $year^{-1}$ of soil, the water holding capacity was assumed to decline 1.9 mm and productivity declined 2%; with severe erosion over time, plant-available water may decline 50 to 75% (*17, 123*). §§Reductions in soil biota were assumed to reduce infiltration of water and reduce organic matter recycling. ‖‖Percentages do not add up because the impacts of the various factors are interdependent and some overlap exists (for example, organic matter is interrelated with water resources, nutrients, soil biota, and soil depth). This loss would occur if lost nutrients and water were not replaced. ¶¶Table 4.

Table 3. Initial effects of factors contributing to reduced corn yield by means of soil erosion of 17 tons ha^{-1} $year^{-1}$ (10 tons ha^{-1} $year^{-1}$ by water and 7 tons ha^{-1} $year^{-1}$ by wind).

Factors	Quantities Lost	Yield Loss (%)
Water runoff	75 mm*	7*
Nitrogen†	15 kg	
Phosphorus†	0.6 kg	2.4¶
Potassium†	123 kg	
Soil depth	1.4 mm‡	0.3‡
Organic matter	2 tons‖	0.2‖
Water holding capacity	0.1 mm§	0.1§
Soil biota	–	0.1#
Total		8**

*Based on a water erosion rate of about 10 tons ha^{-1} $year^{-1}$ on 5% sloping land under conventional tillage, water loss would be nearly 100 mm (*57–60, 124*). A conservative loss of 75 mm was assumed, and based on this water loss, the estimated yield reduction was 7% (*125–127*). †Total nutrients lost are based on the results of Troeh *et al.* (*50*) but reduced as a result of the nutrients that would not be immediately available because of a shortage of time for mineralization (*17*). ‡Based on a bulk density of 1.25 g cm^{-1} and reduced yield of 6% per 2.5 cm of soil (*122*). §Water holding capacity of the soil was calculated to be reduced by 0.1 mm on the basis of the loss of 17 tons ha^{-1} $year^{-1}$ (*17*). ‖Based on a 4% organic matter content of the soil and an enrichment factor of 3; the yield loss is minimal initially but is significant in the long term. The loss of N, P, and K nutrients was estimated to reduce yield by 2.4% (*128*). #Reductions in soil biota were assumed to reduce infiltration of water and reduce organic matter recycling but have a minimal impact on yield for a single year. **This estimated loss occurs after the loss of 17 tons ha^{-1} $year^{-1}$. Percentages do not add up because the impacts of the various factors are interdependent and overlap exists (for example, organic matter is interrelated with water resources, nutrients, soil biota, and soil depth).

soil organic matter, biota, soil depth, and water-holding capacity in some cases cannot be replaced by those interventions.

Erosion Costs

Energy costs. About 6% of the total amount of energy spent in the United States is used in agriculture. Assuming an average erosion rate of 17 tons ha^{-1} $year^{-1}$ for combined wind and water erosion, we estimate that the on-site and off-site impacts of soil erosion and associated rapid water runoff require an additional expenditure of 1.6×10^6 kcal of fossil energy per hectare per year (Table 2). This suggests that about 10% of all the energy used in U.S. agriculture today is spent just to offset the losses of nutrients, water, and crop productivity caused by erosion. Although developed countries are currently using fossil energy–based fertilizers, pesticides, and irrigation to mask the damage of soil erosion and to maintain high crop productivity, heavy dependence on fossil fuels is a risk because fossil energy supplies are finite. Developing nations that use intensive agricultural technologies also rely intensively on the use of fossil energy–based fertilizers, pesticides, and irrigation to provide high yields (*43*).

On-site costs. The use of inappropriate agricultural practices and subsequent soil and water loss are responsible for significant economic and environmental on-site costs. The major on-site costs of erosion by both water and wind are those expended to replace the lost nutrients and water (Tables 1 and 2). When erosion by water and wind occurs at a rate of 17 tons ha^{-1} $year^{-1}$, about 75 mm of water and 462 kg of nutrients are lost per hectare (Table 2). In the United States, if water had to be replaced, it would cost about \$30 ha^{-1} $year^{-1}$ to replace by pumping ground water for irrigation and would require the expenditure of about 70 liters of diesel fuel per hectare (assuming that water were available). An additional \$100 ha^{-1} would be required for fertilizers to replace the lost nutrients (Table 2). If the on-site and off-site costs are summed, erosion costs the United States a total of about \$196 ha^{-1} (Table 2). In other parts of the world, where irrigation is not possible or fertilizers are too costly, the price of erosion is paid in reduced food production.

In the United States, an estimated 4×10^9 tons of soil and 130×10^9 tons of water are lost from the 160×10^6 ha of cropland each year. This translates into an on-site economic loss of more than \$27 billion each year, of which \$20 billion is for replacement of nutrients (*50*) and \$7 billion for lost water and soil depth (Table 2). The most significant component of this cost is the loss of soil nutrients.

The costs of erosion are also high in other regions of the world. In Java, for example, on-farm losses of productivity related to erosion are estimated to cost the economy \$315 million per year (*83*). The 6.6×10^9 tons of Indian soil (*14*) lost each year contains 5.4×10^6 tons of fertilizer worth \$245 million (*84*). Furthermore, up to half of the amount of fertilizers applied each year in areas of India characterized by heavy rainfall during the southwest monsoon is lost as a result of ammonia volatilization and leaching (*85*). In Costa Rica, yearly erosion from farm and pasture land removes nutrients worth 17% of the crop value and 14% of the value of livestock products (*86*).

In addition to substantial economic losses of nutrients and water, erosion causes significant ecological damage. The removal of soil may affect plant composition and deplete soil biodiversity. Some studies of the effects of erosion focus only on changes in soil depth. In such studies, the importance of biodiversity, organic matter, and the other complex of interdependent variables is overlooked. As a result, Lal (*87*) reports that such studies significantly underestimate the impact of soil erosion. Studies on reduced soil depth report crop yield reductions of only 0.13 to 0.39% per centimeter of soil lost (*88, 89*).

Off-site costs. Erosion not only damages the immediate agricultural area where it occurs but also negatively affects the surrounding environment. Off-site problems include roadway, sewer, and basement siltation, drainage disruption, undermining of foundations and pavements, gullying of roads, earth dam failures, eutrophication of waterways, siltation of harbors and channels, loss of reservoir storage, loss of wildlife habitat and disruption of stream ecology, flooding, damage to public health, plus increased water treatment costs (*90*).

The most serious of off-site damages are caused by soil particles entering the water systems (*91*). Of the billions of tons of soil lost from U.S. cropland each year, about 60% is deposited in streams and rivers (*13*). These sediments harm aquatic plants and other organisms by contaminating the water with soil particles along with fertilizer and pesticide chemicals, which adversely alter habitat quality (*92*).

Siltation is a major problem in reservoirs because it reduces water storage and electricity production and shortens the lifetime and increases the maintenance costs of dams. About 880×10^6 tons of agricultural soils are deposited into American reservoirs and aquatic systems each year, reducing their flood-control benefits, clogging waterways, and increasing operating costs of water treatment facilities (*4*). To maintain navigable waterways, the United States annually spends over \$520 million to dredge soil sediments from waterways (*93*).

Heavy sedimentation frequently leads to river and lake flooding (*2*). 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, Missouri, and other rivers located in the central United States. The combined damage of the 1993 flood to crops and homes was assessed by the government to be \$20 billion (*94*).

Wind erosion produces significant off-site damage and costs. It is estimated that household property damage from the sandblasting of automobiles, buildings, and landscapes by blown soil particles and maintenance costs total over \$4 billion per year in the United States (*95–97*). In addition, the removal of accumulated soil from public and private buildings, roads, and railways similarly results in costs of over \$4 billion per year (*95, 96*).

An example of the magnitude of wind erosion is found in New Mexico, where about two-thirds of the land is used for agri-

Table 4. Damages by wind and water erosion and the cost of erosion prevention each year.

Type of damage	Cost (millions of dollars)
*Wind erosion**	
Exterior paint	18.5
Landscaping	2,894.0
Automobiles	134.6
Interior, laundry	986.0
Health	5,371.0†
Recreation	223.2
Road maintenance	1.2
Cost to business	3.5
Cost to irrigation and conservation districts	0.1
Total wind erosion costs	9,632.5
Water erosion‡	
In-stream damage	
Biological impacts	No estimate
Recreational	2,440.0
Water-storage facilities	841.8
Navigation	683.2
Other in-stream uses	1,098.0
Subtotal in-stream	5,063.0
Off-stream effects	
Flood damages	939.4
Water-conveyance facilities	244.0
Water-treatment facilities	122.0
Other off-stream uses	976.0
Subtotal off-stream	2,318.0
Total water erosion costs	7,381.0
Total costs of wind and water erosion damage	17,013.5§
Cost of erosion prevention‖	8,400
Total costs (on and off-site)¶	44,399.0
Benefit/cost ratio	5.24

*(*95–97, 129*). †Health estimates are partly based on Lave and Seskin (*130*). ‡(*93, 96, 97, 129*). §Agriculture accounts for about two-thirds of the off-site effects. ‖See text. ¶The total on-site costs are calculated to be \$27 billion (see Table 3 and text).

culture, including grazing. The total off-site erosion costs in this state, including health and property damage, are estimated to be $465 million annually (95). If we assume similar erosion costs in the western United States, the total off-site costs from wind erosion alone could be as great as $9.6 billion each year in the United States (Table 4).

Combined on-site and off-site effects. The cost of all off-site environmental impacts of U.S. soil erosion, most of which is from agriculture, is estimated to be about $17 billion per year (1992 dollars) (Table 4). An additional yearly loss of $27 billion is attributed to reduced soil productivity. If off-site and on-site costs are combined, the total cost of erosion from agriculture in the United States is about $44 billion per year (Table 4), or about $100 per hectare of cropland and pasture. This erosion cost increases production costs by about 25% each year.

Of the 75×10^9 tons of soil eroded worldwide each year (2), about two-thirds come from agricultural land. If we assume a cost of $3 per ton of soil for nutrients (50), $2 per ton for water loss (Table 2), and $3 per ton for off-site impacts (Table 4), this massive soil loss costs the world about $400 billion per year, or more than $70 per person per year.

Erosion Control Technologies

Reliable and proven soil conservation technologies include ridge-planting, no-till cultivation, crop rotations, strip cropping, grass strips, mulches, living mulches, agroforestry, terracing, contour planting, cover crops, and windbreaks (98). Although the specific processes vary, all conservation methods reduce erosion rates by maintaining a protective vegetative cover over the soil, which is often accompanied by a reduction in the frequency of plowing. Ridge-planting, for example, reduces the need for frequent tillage and also leaves vegetative cover on the soil surface year round, and crop rotations ensure that some part of the land is continually covered with vegetation. Each conservation method may be used separately or in combination with other erosion-control techniques. To determine the most advantageous combination of appropriate conservation technologies, the soil type, specific crop or pasture, slope, and climate (rainfall and wind intensity), as well as the socioeconomics of the people living in a particular site must be considered.

The implementation of appropriate soil and water conservation practices has the potential to reduce erosion rates from 2 to 1000-fold and water loss from 1.3 to 21.7-fold (Tables 1 and 5). Conservation technologies also significantly reduce nutrient loss. For example, when corn residue cover was increased by 10, 30, and 50%, the amount of nitrogen lost in surface runoff was reduced by 68, 90, and 99%, respectively (99).

By substantially decreasing soil and nutrient loss, conservation technologies preserve the soil's fertility and enable the land to sustain higher crop yields. In many instances, the use of conservation technologies may actually increase yields (100). Contour planting, for example, has increased cotton yields by 25% (Texas), corn yields by 12.5% (Missouri), soybeans by 13% (Illinois), and wheat by 17% (Illinois) (101–103). On U.S. land with a 7% slope, yields from cotton grown in rotation increased by 30%, and erosion was reduced by nearly one-half (104). In areas where winds are strong, the establishment of tree and shrub shelterbelts helps reduce wind energy by as much as 87% and thereby decreases erosion by as much as 50% (50).

Table 5. Annual soil loss (tons per hectare) by crop and technology in the United States.

Technology	State	Soil loss (tons ha^{-1})
Corn		
Conventional, continuous (*131*)	MO	47
Conventional, plow-disk (*132*)	IN	47
Conventional, plow-disk (*132*)	OH	27
Conventional, continuous (*133*)	PA	20
Conservation, rotation (*133*)	PA	7
Conservation, contour (*57*)	IL	6
Conservation, no-till (*134*)	MS	0.3
Soybeans		
Conventional (*135*)	MS	36
Conservation, rotation (*135*)	MS	9
Conservation, no-till (*67*)	GA	0.02
Cotton		
Conventional (*136*)	MS	91
Conservation, no-till (*136*)	MS	1.3
Wheat		
Conventional (*137*)	WA	22
Conservation, mulch (*138*)	MS	1.7
Natural vegetation		
Undisturbed grass (*18*)	KS	0.07
Undisturbed forest (*139*)	NH	0.02

Conclusion

We estimate that it would take an investment of $6.4 billion per year ($40 per hectare for conservation) to reduce U.S. erosion rates from about 17 tons ha^{-1} year^{-1} to a sustainable rate of about 1 ton ha^{-1} year^{-1} on most cropland. To reduce erosion on pastureland, the United States would have to spend an additional $2.0 billion per year ($5 per hectare for conservation) (30, 105–107) (Table 4). The total investment for U.S. erosion control would be about $8.4 billion per year. Given that erosion causes about $44 billion in damages each year, it would seem that a $8.4 billion investment is a small price to pay: For every $1 invested, $5.24 would be saved (Table 4). This small investment would reduce U.S. agricultural soil loss by about 4×10^9 tons and help protect our current and future food supply.

Currently, the United States spends $1.7 billion per year in the Conservation Reserve Program to remove highly erodible land from production, and this saves about 584×10^6 tons of soil each year (108). Therefore, in this system $2.91 is invested to save 1 ton of soil, whereas in our proposed conservation system, we assume a cost of $2.10 per ton of soil saved.

When economic costs of soil loss and degradation and off-site effects are conservatively estimated into the cost/benefit analyses of agriculture, it makes sound economic sense to invest in programs that are effective in the control of widespread erosion. Human survival and prosperity depend on adequate supplies of food, land, water, energy, and biodiversity. Infertile, poor-quality land will not sustain food production at the levels required by the growing world population. We should heed President Roosevelt's (109) warning that "A nation that destroys its soils, destroys itself."

REFERENCES AND NOTES

1. R. Lal and B. A. Stewart, *Soil Degradation* (Springer-Verlag, New York, 1990).
2. N. Myers, *Gaia: An Atlas of Planet Management* (Anchor and Doubleday, Garden City, NY, 1993).
3. P. Buringh, in *Food and Natural Resources*, D. Pimentel and C. W. Hall, Eds. (Academic Press, San Diego, 1989), pp. 69–83.
4. World Resources Institute, *World Resources 1992–1993* (Oxford Univ. Press, New York, 1992).
5. D. Pimentel, R. Harman, M. Pacenza, J. Pecarsky, M. Pimentel, *Popul. Environ.* **15**, 347 (1994).
6. R. Lal, in (3), pp. 85–140.
7. D. Pimentel, Ed., *World Soil Erosion and Conservation* (Cambridge Univ. Press, Cambridge, 1993).
8. *World Can Cut Hunger Rate in Half*, World Bank press release, Washington, DC, 29 November 1993.
9. J. G. Soetn, *Towards an Effective and Operational International Convention on Desertification* (International Negotiating Committee, International Convention on Desertification, United Nations, New York, 1994).
10. M. Giampietro and D. Pimentel, *The NPG Forum* (Negative Population Growth, Teaneck, NJ, October 1993).
11. A. Gore, *The Earth Times* **1**, 31 (15 June 1994).
12. N. Myers, *Deforestation Rates in Tropical Forests and their Climatic Implications* (Friends of the Earth Report, London, 1989).
13. U.S. Department of Agriculture, *The Second RCA Appraisal: Soil, Water, and Related Resources on Nonfederal Land in the United States: Analysis of Conditions and Trends* (U.S. Department of Agriculture, Washington, DC, 1989).
14. R. Lal, in (7), pp. 7–26.
15. Worldwatch Institute, *State of the World 1988* (Worldwatch Institute, Washington, DC, 1988).
16. C. J. Barrow, *Land Degradation* (Cambridge Univ. Press, Cambridge, 1991).
17. F. R. Troeh and L. M. Thompson, *Soils and Soil Fertility* (Oxford Univ. Press, New York, ed. 5, 1993).
18. H. H. Bennett, *Soil Conservation* (McGraw-Hill, New York, 1939).
19. E. Roose, in *Conservation Farming on Steep Lands*

(Soil and Water Conservation Society, Ankeny, IA, 1988), pp. 130–131.
20. D. Pimentel *et al.*, *Science* **194**, 149 (1976).
21. U.S. Department of Agriculture, *Agriculture and the Environment* (U.S. Department of Agriculture, Economic Research Service, Washington, DC, 1971).
22. L. K. Lee, *J. Soil Water Conserv.* **45**, 622 (1990).
23. N. W. Hudson, in *Soil Erosion and Conservation in the Tropics* (Spec. Publ. 43, American Society of Agronomists, Madison, WI, 1982), pp. 121–133.
24. R. Lal, in *Quantification of the Effect of Erosion on Soil Productivity in an International Context*, F. R. Rijsberman and M. G. Wolman, Eds. (Delft Hydraulics Laboratory, Delft, Netherlands, 1984), pp. 70–94.
25. L. Hood and J. K. Morgan, *Sierra Club Bull.* **57**, 4 (1972).
26. E. K. Byington, *Grazing Land Management and Water Quality* (American Society of Agronomists and Crop Scientists Society of America, Harpers Ferry, WV, 1986).
27. J. Risser, *Smithsonian* **11**, 120 (March, 1981).
28. G. A. Klee, *Conservation of Natural Resources* (Prentice-Hall, Englewood Cliffs, NJ, 1991).
29. U.S. Department of Agriculture, *Agricultural Statistics 1967* (Government Printing Office, Washington, DC, 1967).
30. U.S. Department of Agriculture, *Agricultural Statistics 1992* (Government Printing Office, Washington, DC, 1992).
31. R. Lal, *Soil Erosion Problems on an Alisol in Western Nigeria and their Control* (International Institute of Tropical Agriculture, Ibadan, Nigeria, 1976).
32. F. H. Buttel, *Cornell Rural Sociology Bulletin No. 128* (Cornell University, Ithaca, NY, 1982).
33. Office of Technology Assessment, *Impacts of Technology on U.S. Cropland and Rangeland Productivity* (U.S. Congress Office of Technology Assessment, Washington, DC, 1982).
34. F. E. Allison, *Soil Organic Matter and Its Role in Crop Production* (Elsevier, New York, 1973).
35. G. R. Foster, R. A. Young, M. J. M. Ronkens, C. A. Onstad, in (*52*), pp. 137–162.
36. M. Simons, *New York Times*, 29 October 1992, p. A1.
37. J. R. Parrington, W. H. Zoller, N. K. Aras, *Science* **220**, 195 (1983).
38. P. O. Aina, R. Lal, G. S. Taylor, Eds., *Soil Erosion: Prediction and Control* (Soil Conservation Society of America, Ankeny, IA, 1977).
39. U.S. Forest Service, *The Major Range Problems and Their Solution* (U.S. Forest Service, Washington, DC, 1936).
40. A. N. Sharpley and S. J. Smith, in *Cover Crops for Clean Water*, W. L. Hargrove, Ed. (Soil and Water Conservation Society, Ankeny, IA, 1991), p. 41.
41. Wen Dazhong, in (*7*), pp. 63–86.
42. L. McLaughlin, thesis, Cornell University (1991).
43. H. W. Kendall and D. Pimentel, *Ambio* **23**, 198 (1994).
44. Statistical data, *FAO Q. Bull. Stat.* **5**, 1 (1992).
45. W. W. Frye, S. A. Ebelhar, L. W. Murdock, R. L. Bevins, *Soil Sci. Soc. Am. J.* **46**, 1051 (1982).
46. K. R. Olson and E. Nizeyimana, *J. Prod. Agric.* **1**, 13 (1988); D. L. Schertz, W. C. Moldenhauert, S. J. Livingston, F. A. Weesies, E. A. Hintz, *J. Soil Water Conserv.* **44**, 604 (1989), G. W. Landale, J. E. Box, R. A. Leonard, A. P. Barnett, W. G. Fleming, *ibid.* **34**, 226 (1979).
47. D. L. Mokma and M. A. Sietz, *J. Soil Water Conserv.* **47**, 325 (1992).
48. H. E. Dregne, *ibid.*, p. 8.
49. S. A. El-Swaify, W. C. Moldenhauer, A. Lo, *Soil Erosion and Conservation* (Soil Conservation Society of America, Ankeny, IA, 1985).
50. F. R. Troeh, J. A. Hobbs, R. L. Donahue, *Soil and Water Conservation* (Prentice-Hall, Englewood Cliffs, NJ, 1991).
51. National Soil Erosion–Soil Production Research Planning Committee, *J. Soil Water Conserv.* **36**, 82 (1981).
52. R. F. Follett and B. A. Stewart, Eds., *Soil Erosion and Crop Productivity* (American Society of Agronomy and Crop Science Society of America, Madison, WI, 1985).
53. M. Falkenmark, in (*3*), pp. 164–191.
54. L. Leyton, in *Plant Research and Agroforestry*, P. A. Huxley, Ed. (International Council for Research in Agroforestry, Nairobi, Kenya, 1983), pp. 379–400.
55. R. P. Waldren, in *Crop-Water Relations*, I. D. Teare and M. M. Peet, Eds. (Wiley, New York, 1983), pp. 187–212.
56. R. H. Donahue, R. H. Follett, R. N. Tulloch, *Our Soils and Their Management*. (Interstate, Danville, IL, 1990).
57. C. A. Van Doren, R. S. Stauffer, E. H. Kidder, *Soil Sci. Soc. Am. Proc.* **15**, 413 (1950).
58. R. C. Wendt and R. E. Burwell, *J. Soil Water Conserv.* **40**, 450 (1985).
59. R. C. Wendt, E. E. Alberts, A. T. Helmers, *Soil Sci. Soc. Am. J.* **50**, 730 (1986).
60. C. E. Murphee and K. C. McGregor, *Trans. ASAE* **34**, 407 (1991).
61. H. A. Elwell, *Zimbabwe Sci. News* **19**, 27 (1985).
62. M. Alexander, *Introduction to Soil Microbiology* (Wiley, New York, 1977).
63. P. N. Bhatt, *Soil Conserv. Dig.* **5**, 37 (1977).
64. R. Lal, in *Nitrogen Cycling in West African Ecosystems*, T. Rosswall, Ed. (Reklan and Katalogtryck, Uppsala, Sweden, 1980), pp. 31–38.
65. A. Young, *Agroforestry for Soil Conservation* (CAB International, Wallingford, UK, 1989).
66. K. Chaney and R. S. Swift, *J. Soil Sci.* **35**, 223 (1984).
67. G. W. Langdale, L. T. West, R. R. Bruce, W. P. Miller, A. W. Thomas, *Soil Technol.* **5**, 81 (1992).
68. R. F. Follett, S. C. Gupta, P. G. Hunt, in *Soil Fertility and Organic Matter as Critical Components of Production Systems* (Soil Science Society of America and American Society of Agronomy, Madison, WI, 1987).
69. A. Young, *Outlook Agric.* **19**, 155 (1990)
70. H. L. Barrows and V. J. Kilmer, *Adv. Agron.* **15**, 303 (1963).
71. R. E. Lucas, J. B. Holtman, L. J. Connor, in *Agriculture and Energy*, W. Lockeretz, Ed. (Academic Press, New York, 1977), pp. 333–351.
72. M. Wood, *Soil Biology* (Blackie, Chapman and Hall, New York, 1989).
73. E. Lee and R. C. Foster, *Aust. J. Soil Res.* **29**, 745 (1991).
74. D. Pimentel et al., *BioScience* **30**, 750 (1980).
75. J. A. Van Rhee, *Plant Soil* **22**, 43 (1965).
76. O. Atlavinyte, *Pedobiologia* **4**, 245 (1964).
77. ———, *ibid.* **5**, 178 (1965).
78. W. S. Reid, in (*52*), pp. 235–250.
79. S. P. Teotia, F. L. Duky, T. M. McCalla, *Effect of Stubble Mulch on Number and Activity of Earthworms* (Nebraska Experiment Station Research Bulletin 165, Lincoln, NE, 1950).
80. G. A. E. Ricou, in *Grassland Ecosystems of the World: Analysis of Grasslands and Their Uses*, R. T. Coupland, Ed. (Cambridge Univ. Press, Cambridge, 1979), pp. 147–153.
81. N. W. Hudson, *Soil Conservation* (Cornell Univ. Press, Ithaca, NY, ed. 2, 1981).
82. P. W. Chapman, F. W. Fitch, C. L. Veatch, *Conserving Soil Resources: A Guide to Better Living* (Smith, Atlanta, GA, 1950).
83. W. Magrath and P. Arens, "The Costs of Soil Erosion on Java: A Natural Resource Accounting Approach," *Environment Department Working Paper No. 18* (World Bank, Washington, DC, 1989).
84. H. P. Chaudhary and S. K. Das, *J. Indian Soc. Soil Sci.* **38**, 126 (1990).
85. M. S. Swaminathan, personal communication.
86. R. Repetto, *Sci. Am.* **266**, 94 (June 1992).
87. R. Lal, in *Soil Erosion Research Methods* (Soil and Water Conservation Society, Ankeny, IA, 1988), pp. 187–200.
88. P. N. Crosson and T. T. Stout, *Productivity Effects of Cropland Erosion in the United States* (Resources for the Future, Washington, DC, 1983).
89. F. J. Pierce, R. H. Dowdy, W. A. P. Graham, *J. Soil Water Conserv.* **39**, 131 (1984).
90. D. M. Gray and A. T. Leiser, *Biotechnical Slope Protection and Erosion Control* (Kreiger, Malabar, FL, 1989).
91. U.S. Department of Agriculture, *Fact Book of Agriculture* (U.S. Department of Agriculture, Office of Public Affairs, Washington, DC, 1990).
92. E. H. Clark, in *Soil Loss: Processes, Policies, and Prospects*, J. M. Harlin and G. M. Bernar[illegible] (Westview, New York, 1987), pp. 59–89.
93. E. H. Clark, *J. Soil Water Conserv.* **40**, 19 [illegible]
94. W. Allen, *St. Louis Post Dispatch*, 27 Januar[illegible] p. 01B.
95. P. C. Huszar and S. L. Piper, in *Off-Site C[illegible] Soil Erosion: The Proceedings of a Sym[illegible]* (Conservation Foundation, Washington, DC, [illegible] pp. 143–166.
96. Soil Conservation Service, *Wind Erosion [illegible] Nov. 1992–May 1993* (Soil Conservation S[illegible] U.S. Department of Agriculture, Washingto[illegible] 1993).
97. S. L. Piper, personal communication.
98. M. R. Carter, Ed., *Conservation Tillage in Te[illegible]ate Agroecosystems* (Lewis, Boca Rato[illegible] 1994).
99. R. G. Palis, G. Okwach, C. W. Rose, P. G. Sa[illegible] *Aust. J. Soil Res.* **28**, 623 (1990).
100. P. Faeth, *Agricultural Policy and Sustai[illegible] Case Studies from India, Chile, the Philippi[illegible] the United States* (World Resources In[illegible] Washington, DC, 1993).
101. E. Burnett and C. E. Fisher, *Soil Sci. Soc. Am.* [illegible] **18**, 216 (1954).
102. D. D. Smith, *J. Am. Soc. Agron.* **38**, 810 (19[illegible]
103. E. L. Sauer and H. C. M. Case, *Soil Conser[illegible] Pays Off: Results of Ten Years of Conser[illegible] Farming in Illinois* (Univ. of Illinois Agriculture E[illegible]iment Station Bulletin, Urbana, IL, 1954).
104. B. H. Hendrickson, A. P. Barnett, J. R. Carre[illegible] E. Adams, *USDA Tech. Bull. No. 1281* (U.[illegible]partment of Agriculture, Washington, DC, [illegible]
105. R. H. Hart, M. J. Samuel, P. S. Test, M. A. [illegible] *Range Manage.* **41**, 282 (1988).
106. C. A. Taylor Jr., N. E. Garza Jr., T. O. Br[illegible] *Rangelands* **15**, 53 (1993).
107. J. M. Fowler, A. Torell, G. Gallacher, *J. Range [illegible]age.* **47**, 155 (1994).
108. U.S. Department of Agriculture, *Agricultural S[illegible]tics 1991* (Government Printing Office, Was[illegible]ton, DC, 1991).
109. F. D. Roosevelt, *Letter from President to Gove[illegible]* (White House, Washington, DC, 26 February 1[illegible]
110. J. W. Ketcheson and J. J. Onderdonk, *Agro[illegible]* **65**, 69 (1973).
111. S. D. Klausner, P. J. Zwerman, D. F. Ellis, [illegible] *ron. Qual.* **3**, 42 (1974).
112. G. W. Musgrave and O. R. Neal, *Am. Geo[illegible] Union Trans.* **18**, 349 (1937).
113. J. Ketcheson, *J. Soil Water Conserv.* **32**, 57 (1[illegible]
114. R. G. Spomer, R. F. Piest, H. G. Heinemann, *Tr[illegible] ASAE* **19**, 108 (1976).
115. G. C. Schuman, R. G. Spomer, R. F. Piest, *Soil Soc. Am. Proc.* **37**, 424 (1973).
116. A. Mohammad and F. A. Gumbs, *J. Agric. [illegible] Res.* **27**, 481 (1982).
117. G. F. McIsaac and J. K Mitchell, *Trans. ASAE* [illegible] 465 (1992).
118. W. Hinz, *Ariz. Farmer-Stockman* **64**, 16 (19[illegible]
119. National Academy of Sciences, *Soil and W[illegible] Quality: An Agenda for Agriculture* (National Ac[illegible]emy of Sciences, Washington, DC, 1993).
120. J. C. Batty and J. Keller, in (*121*), pp. 35–44.
121. D. Pimentel, Ed., *Handbook of Energy Utilizatio[illegible] Agriculture* (CRC Press, Boca Raton, FL, 1980
122. L. Lyles, *J. Soil Water Conserv.* **30**, 279 (1975)
123. D. L. Schertz, W. C. Moldenhauer, S. J. Livings[illegible] G. A. Weesies, E. A. Hintz, *ibid.* **44**, 604 (1989)
124. L. A. Kramer, *Trans. ASAE* **29**, 774 (1986).
125. R. J. Hanks, in *Limitations to Efficient Water Us[illegible] Crop Production*, H. M. Taylor, W. R. Jordan, T[illegible] Sinclair, Eds. (American Society of Agronomy, C[illegible] Science Society of America, and Soil Science [illegible]ciety of America, Madison, WI, 1983), pp. 3[illegible] 411.
126. J. Shalhavet, A. Mantell, H. Bielorai, D. Shim[illegible] *Irrigation of Field and Orchard Crops Under Se[illegible] Arid Conditions* (Pergamon, Elmsford, NY, 197[illegible]
127. R. A. Feddes, in *Crop Water Requirements*, Int[illegible]national Conference, Versailles, France, 11 to [illegible] September 1984 [United Nations Educatio[illegible] Scientific, and Cultural Organization (UNESC[illegible] under the auspices of the Food and Agricult[illegible] Organization and the World Meteorological Or[illegible]

AGRICULTURE

Erosion Study Finds High Price for Forgotten Menace

It was Scarlett O'Hara in *Gone With the Wind* who mused that land is "the only thing in the world that lasts." Scarlett O'Hara never read David Pimentel. On page 1117 of this issue, the Cornell University scientist and his colleagues present the most comprehensive effort yet to add up the costs of soil erosion by wind and water. Their bottom line is eye-popping: $44 billion every year in direct damage to agricultural lands and "indirect damage" to waterways, infrastructure, and health in the United States, and nearly $400 billion in damage worldwide. Not only does land not last, Pimentel finds, but its demise comes with a hefty price tag.

Pimentel's spectacular numbers are drawing mixed reviews from agricultural and economic researchers. "The magnitudes are out of alignment with what we have generally found to be the case," says John Stierna, an agricultural economist at the U.S. Department of Agriculture's (USDA's) Natural Resources Conservation Service. "Some of his numbers are a factor of 2 to 3 too high." But others say they are right on the mark. "I think some folks who are not familiar with the soil-erosion literature are going to be a little surprised," says Marty Bender, an agronomist at the Land Institute in Salina, Kansas, which studies innovative farming techniques. "But the data is there."

And the message could have some reverberations in Washington. The 1985 Food Security Act, which requires farmers to follow conservation guidelines such as contour farming and reduced tillage or risk losing federal subsidies, is now up for renewal, and sources close to the Senate Agriculture Committee predict intense pressure to roll back the law's environmental provisions. If the Cornell group's dire assessment of the costs of erosion is accepted, say these sources, it could be a powerful argument in favor of preserving the anti-erosion requirements.

It's easy to get complacent about erosion, notes Pimentel; the Dust Bowl, after all, is a fading memory, and modern farming techniques have greatly reduced the kind of erosion that corrugates a field with rills and gullies. But as early as 1929, just before the Dust Bowl, USDA soil scientist Hugh Hammond Bennett realized that the most devastating form of erosion is the least obvious: Wind and rain can strip away soil in extensive sheets, leaving little visible evidence of the damage.

Sheet erosion tends to be worse on large fields that have few windbreaks or natural buffers to prevent soil from washing off, says Pimentel, and some recent practices, like plowing up grassed strips at the edges of fields to accommodate larger machinery, may have increased it. In a night of heavy rain, the process can strip 5 or 6 tons of soil from an acre of cropland. "That's one millimeter of soil [lost], and if you walk out the next morning, you wouldn't know it," he says. "Erosion is one of those things that nickels and dimes you to death."

Down the drain. The most devastating forms of soil erosion are less obvious, however.

Pimentel's team totted up those nickels and dimes by drawing on dozens of individual studies published over the last several decades. Many of them estimate damage done far from the site of the erosion. Erosion by water leads to billions of dollars in costs when rivers, canals, lakes, and reservoirs become clogged with sediment or polluted with the fertilizers and pesticides that cling to the soil particles. Heavily sedimented rivers also increase the severity of floods—some researchers, for example, think silted river channels exacerbated the 1993 Midwest flooding. Wind erosion takes a toll on paints and mechanical equipment, buries roads and railways, and contributes to respiratory ailments.

Estimating the cost of on-site damage is "trickier," says Richard Harwood, a professor of sustainable agriculture at Michigan State University—and it's also the focus of most of the controversy. These costs are elusive, he says, because the loss of productive potential due to erosion can be masked for a time by increased inputs of fertilizer, irrigation, and higher yielding plant varieties. The price exacted by erosion is hidden in the cost of these inputs, and few researchers have tried to tease it out.

Pimentel and his colleagues worked around this problem by looking instead at the physical toll that erosion takes on croplands. Based on estimates of how much nutrient-rich soil organic matter is eroded each year, the team tried to estimate the market value of those lost nutrients—the cost of replacing them with fertilizers—and came up with a figure of $20 billion a year. They also took into account the loss of soil depth and soil biota such as insects and earthworms. Together with the loss of organic matter, these reduce the soil's ability to take in water, increasing the need for irrigation or reducing crop yields.

When the Cornell group added in these losses, the total on-site cost of erosion reached $27 billion a year in the United States. Perhaps more alarming, Pimentel's team found that the loss of nutrients and water retention drives a startling decline in productive potential. They found that moderate erosion, sustained for 20 years, can reduce the potential yield of good agricultural land by 20%.

Pimentel's accounting hasn't convinced everyone. "If there are two different values, he almost always goes with the big one," says Frederick Troeh, a soil scientist at Iowa State University. Other critics dispute the $20 billion figure for nutrient losses on the grounds that, in rich soils, crops consume only a fraction of the available nutrients each year, so the losses have little immediate effect. Pimentel replies that a loss is a loss, even if it comes out of long-term savings. "This stuff is gone down the Mississippi or the Missouri River," he says. "It's never going to be available—ever."

Erosion's toll might be higher still, says Rattan Lal, a soil scientist at Ohio State University in Columbus, if not for federal programs such as the soil-conservation provisions of the 1985 Food Security Act and the Conservation Reserve Program. But Pimentel and his colleagues say these steps fall short of what is needed. They calculate that an investment of 19 cents in new conservation measures for every dollar of damage would be required to bring soil erosion under control in the United States—a proposed annual outlay of $8.4 billion.

In the cost-cutting environment of Washington, that proposal has little chance of getting a hearing. But even those who disagree with Pimentel's numbers hope his broader message won't be ignored in the upcoming debate. "There are specific [numbers] to quibble about," says Troeh. "But the overall conclusion that erosion is a threat and is often ignored—I very much agree with that."

—James Glanz

SCIENCE

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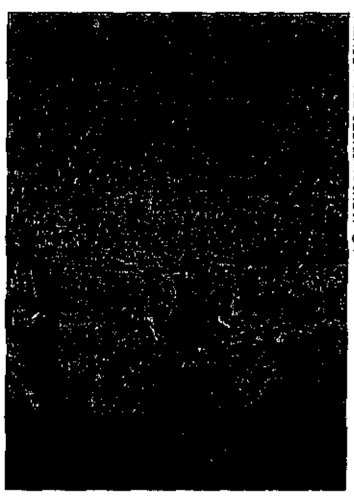
LETTERS

Soil Erosion Estimates and Costs

In their article "Environmental and economic costs of soil erosion and conservation benefits," David Pimentel *et al.* (Articles, 24 Feb., p. 1117) assert that soil erosion is a major threat to the sustainability of agriculture all around the world and more specifically in the United States. In the source (*1*) they cite to support their introductory statement, Lal and Stewart (*2*) state that annual global erosion is about 36 billion tons, 10 billion attributable to natural causes and 26 billion to human activity. Lal and Stewart, in turn, cite a paper by Brown (*3*) as source for the 26-ton figure. In a review of Brown's work, I found (*4*) that his estimate of global erosion is based mainly on erosion estimates in the United States and on an extrapolation of the U.S. experience to the rest of the world. I did not and do not claim that Brown's estimate is wrong but the estimate rests on such thin underpinnings that it cannot be taken seriously.

Until the publication of work by Dregne and Chou (*5*) and Oldeman *et al.* (*6*) in the early 1990s, none of whom are cited by Pimentel *et al.*, there were no reliable estimates of how much erosion is occurring around the world, let alone its productivity consequences (*2, 7–9*). The study by Dregne and Chou (*5*) deals with global degradation of rainfed cropland, irrigated land, and rangeland in dry areas, meaning arid, semi-arid, and dry subhumid climatic zones. Dregne and Chou classified these lands as slightly degraded (0 to 10% loss of productivity), moderately degraded (10 to 25% loss), severely degraded (25 to 50% loss), and very severely degraded (greater than 50% loss). I used their data (*5*) to calculate a weighted average degradation-induced loss of productivity of 11%. This is the cumulative loss over some period of time, which Dregne and Chou do not indicate. But for most of this land the period must be not less than several decades. The annual rate of productivity loss, therefore, would be less than 0.5%.



Soil erosion. Corn field in Missouri in 1994 shows effects of cultivation.

Oldeman *et al.* (*6*) found 1.965 billion hectares of degraded land around the world, 85% of it attributable to water and wind erosion. Thirty-eight percent of the degraded land was lightly degraded, 48% was moderately degraded, and 14% was strongly (or extremely) degraded. Oldeman *et al.* did not assign percentages of productivity loss to their degree-of-degradation categories. I assumed that the percentages correspond to those in the study by Dregne and Chou (*5*), that is, lightly degraded land has lost 0 to 10% of its productivity, and so on; I used the data from the study by Oldeman *et al.* to calculate a weighted average loss of 17%. The estimates of Oldeman *et al.* specifically refer to human-induced land degradation that occurred between the end of World War II and about 1990. The cumulative productivity loss of 17% over this 45 years implies an average annual loss of 0.4%.

Pimentel *et al.* cite a paper by Speth (*10*) as the source for the statement that "About 80% of the world's agricultural land suffers moderate to severe erosion, and 10% suffers slight to moderate erosion." However, Oldeman *et al.* (*6*) show that on a global scale about 1.03 billion hectares of agricultural land have suffered moderate-to-strong degradation because of wind and water erosion. This is less than 25% of the roughly 4.5 billion hectares of land in crops, pasture, and range around the world, and well under a third of the 80% figure given by Pimentel *et al.*

Pimentel *et al.* cite a paper by Barrow (*11*) for their assertion that soil erosion rates are highest in Asia, South America, and Africa, averaging 30 to 40 tons per hectare per year. Barrow states (*11*, p. 209) that the estimates he discusses are crude and that it "probably would be wise to wait until the publication of the GLASOD [Global Assessment of Soil Degradation] maps, sometime after 1990, before trying to get an accurate overview of soil erosion." The GLASOD maps are those prepared by Oldeman *et al.*, published in 1990 (*6*).

Pimentel *et al.* state that over the last 200 years 100 million hectares (about 30%) of U.S. farmland has been abandoned because of erosion, salinization, and waterlogging and cite the U.S. Department of Agriculture

(USDA) (*12*), Bennett (*13*), and Pimentel *et al.* (*14*). In a close reading of the USDA report (*12*), I found nothing about degradation of U.S. land over the last 200 years, and the Bennett citation is a 1939 publication.

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Water erosion. Farm field washing away in Harper County, Kansas, in 1984.

Pimentel *et al.* cite the USDA (*12*) as the source for the statement that the combined effect of water and wind erosion moves an average of 17 tons per hectare per year from U.S. croplands, which figure they then use in cost estimates. Successive USDA surveys (*15*) provide more accurate estimates of cropland erosion for 1982, 1987, and 1992. Pimentel et *al.* do not reference the updated surveys which show that the 1992 rate was 13 tons per hectare per year, almost 25% less than originally reported (*12*).

Pimentel et *al.* state that they have "developed empirical models that incorporate the numerous factors affecting both erosion rates and soil productivity." However, the models are not presented, so the reader is unable to evaluate them. We are told that the models are based on numerical assumptions about rainfall, soil depth, type and slope of soil, percent of soil organic matter, and an annual erosion rate of 17 tons per hectare per year. No sources are given for any of these numbers, although the last evidently is from (*12*) and hence is for 1982. The numbers, and presumably the unspecified models, are used to estimate the annual on-farm per hectare economic costs of losses of soil and water resulting from erosion of 17 tons per hectare per year on conventionally tilled land in corn, over a 20-year period (Pimentel et *al.*'s table 2). This estimate is then multiplied by 160 million hectares, said to be the total amount of cropland in the country, to get an estimate of the annual nationwide on-farm economic costs of cropland erosion. This estimate is $27 billion per year, although the per hectare estimate of on-farm costs of $146 (Pimentel *et al.*'s table 2), when multiplied by 160 million hectares, gives a total cost of $23 billion (not $27 billion).

These procedures, the numbers used, and the results obtained prompt several questions and comments.

1) Why should the assumed conditions with respect to precipitation, soil type, slope, depth, and percent organic matter be representative of cropland in the country as a whole? These conditions are highly variable across regions.

2) How was the $100 per hectare cost of nutrient replacement estimated (Pimentel *et al.*'s table 2)? A source is cited for the losses of nutrients in terms of kilograms, but no information is given about how these losses were valued. The issue is of major importance because nutrient losses account for two-thirds of the total on-farm economic costs. Multiplying average 1992 prices for anhydrous ammonia, the most common form of nitrogen fertilizer, superphosphate (44 to 46% phosphate), and potassium chloride (60% potassium) (*16*, p. 27) by the quantities of lost nutrients shown by Pimentel *et al.* (Pimentel *et al.*'s table 3) gives an estimate of plant-available nutrient losses of about $23 per hectare. Even if the cost is measured by total nutrient losses, that is, by counting nutrients not available to support plant growth in any given year, the total per hectare cost of nutrient losses comes to only about $75, still well below $100.

3) What are we to make of the cost of the erosion-induced losses of water (Pimentel *et al.*'s table 2)? At $30 per hectare per year, this cost is 20% of total on-farm costs. A note in that table says that it is the cost of supplying groundwater for irrigation to replace erosion-induced losses of water from precipitation: "if rainfall were abundant, then this replacement cost would not be necessary." In the main crop-producing areas of the country east of the Great Plains, rainfall is generally adequate to maintain current yields, as indicated by the scant use of irrigation. In those areas the cost of replacing erosion-induced losses of water, as estimated by Pimentel *et al.*, should be zero. Pimentel *et al.* acknowledge this problem, but include the estimated cost of water losses in their calculation of nationwide costs.

Other studies show much lower on-farm costs of soil erosion in the United States than Pimentel *et al.* do. One such study is based on the Erosion Productivity Impact Calculator (EPIC) model developed by USDA soil scientists (*12*). EPIC simulates the productivity effects of soil erosion on soil characteristics and processes, including losses of soil nutrients, water-holding capacity, and acidity (pH). In (*12*), the estimate with EPIC showed the average annual gross on-farm costs of 100 years of cropland erosion in the United States at 1982 rates to be $252 million. In another study (*17*), I used results from the Productivity Index model, developed by soil scientists at the University of Minnesota (*18*), to estimate the annual gross cost of erosion-induced on-farm losses of productivity in the United States to be $500 million to $600 million.

The present rate of cropland erosion in the United States is probably close to 13 tons per hectare per year, not 17. Pimentel *et al.* have greatly overestimated the on-farm per hectare costs of replacing nutrients and water. Their estimate of the nationwide on-farm costs of cropland erosion appears to be greatly overstated, even if their procedures and assumptions are accepted.

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References and Notes

1. N. Myers, *Gaia: An Atlas of Planet Management* (Anchor and Doubleday, Garden City, NY, 1993).
2. R. Lal, in *Soil Degradation*, R. Lal and B. A. Stewart, Eds. (Springer-Verlag, New York, 1990), p. 132.
3. L. Brown, *State of the World 1984* (Worldwatch Institute, W. W. Norton, New York, 1984).
4. P. Crosson, in *Population and Food in the Early 21st Century: Meeting Future Food Demands of Increasing Population*, N. Islam, Ed. (International Food Policy Research Institute, Washington, DC, 1995), pp. 143–159.
5. H. E. Dregne and Nan-Ting Chou, in *Degradation and Restoration of Arid Lands* (Texas Tech Univ., Lubbock, TX, 1992), pp. 249–282.
6. L. Oldeman, R. Hakkeling, W. Sombroeck, *World Map of the Status of Human-Induced Soil Degradation: An Explanatory Note* (International Soil Reference and Information Center, Wageningen, The Netherlands, and United Nations Environment Programme, Nairobi, Kenya, 1990).
7. R. Nelson, *Dryland Management: The Land Degradation Problem* (Environment Department Working Paper No. 8, World Bank, Washington, DC, 1988).
8. H. E. Dregne, in *Challenges in Dryland Agriculture: A Global Perspective*, P. Unger, T. Sneed, W. Jordan, R. Jensen, Eds. (Texas Agricultural Experiment Station, Amarillo/Bushland, TX, 1988), pp. 610–612.
9. S. El-Swaify, E. Dangler, C. Armstrong, *Soil Erosion by Water in the Tropics* (Univ. of Hawaii, Honolulu, 1982).
10. J. G. Speth, *Towards an Effective and Operational International Convention on Desertification* (International Negotiating Committee, International Convention on Desertification, United Nations, New York, 1994).
11. C. J. Barrow, *Land Degradation* (Cambridge Univ. Press, Cambridge, UK, 1991).
12. *The Second RCA Appraisal: Soil, Water, and Related Resources on Nonfederal Land in the United States* (U.S. Department of Agriculture, Washington, DC, 1989).
13. H. H. Bennett, *Soil Conservation* (McGraw-Hill, New York, 1939).
14. D. Pimentel *et al.*, *Science* **194**, 149 (1976).
15. *Summary Report 1992 National Resources Inventory* (Soil Conservation Service, U.S. Department of Agriculture, Washington, DC, 1994).
16. H. H. Taylor, *Fertilizer Use and Price Statistics, 1960–93* (Statistical Bulletin No. 893, Economic Re-

search Service, U.S. Department of Agriculture, Washington, DC, 1994).
17. P. Crosson, in *Agriculture and the Environment*, T. Phipps, P. Crosson, K. Price, Eds. (Resources for the Future, Washington, DC, 1986), pp. 35–73.
18. F. Pierce, R. Dowdy, W. Larson, W. Graham, *J. Soil Water Conserv.* **39**, 131 (1984).

Response: Crosson indicates that the estimate of 75 billion metric tons per year of world soil lost to erosion, worldwide, is too high (*1*). The estimated soil loss in the United States is nearly 4 billion tons per year on nonfederal land (*2*) plus an estimated 0.5 billion tons on federal lands. The United States has about 11% of the world's arable land and approximately the same percentage of pasture land (*3*). Therefore, assuming that the rest of the world suffers similar rates of erosion, the total global soil loss would be approximately 40 billion tons per year. However, as pointed out in our report, soil erosion rates in Asia, Africa, and South America are about double those of the United States (*4, 5*). Taking these higher rates of erosion into consideration, the estimated 75 billion tons per year of eroded soil seems reasonable.

The estimate that 80% of the world's agricultural land suffers from moderate to severe soil degradation (*6*) is consistent with several other investigations (*4, 5*).

Bennett (*7*) in 1939 reported that about 80 million hectares of cropland either had been ruined, severely damaged, or had lost one-half of all topsoil. Since 1939, U.S. agricultural land has continued to erode and be lost to production (*8*). Our estimate, that 100 million hectares (about 30%) of U.S. farmland has been abandoned, is conservative. Lal (*9*) reports that an estimated 2.0 billion hectares of once productive agricultural land has been degraded or destroyed during the history of agriculture worldwide. Agricultural land continues to be degraded and abandoned because of erosion and is resulting in the rapid and continued spread of agriculture into world forest-lands (*10*).

We did not see the latest USDA (*11*) survey that was published in 1994 on soil erosion because our paper was submitted during the summer of 1994. We are delighted to know that during the past 10 years soil erosion on cropland has declined by 25%. However, the current erosion rate of 13 tons per hectare per year is still 13 times above the soil sustainability rate. Also, the rates of soil erosion on pastures and rangelands in the survey did not decline and remain a serious threat to these agricultural lands (*11*).

Crosson states that rainfall east of the Great Plains, including the "corn belt," is adequate for corn production. However, adequate rainfall is not the same as optimum. Corn production even in the corn belt usually suffers from water shortages during the summer growing season (*12*). Thus, the increased water loss associated with soil erosion has a negative impact on corn yields.

We stated in our article explicitly how the $27-billion-per-year estimated nationwide on-farm economic cost of cropland erosion was calculated. This was based on a $20 billion replacement value for soil nutrients (*8*) and $7 billion for loss of water and reduced soil depth. We stated in detail the assumptions and documented the sources for the field experimental data used in our tables 2 and 3. We agree with Crosson that soil type, precipitation, slope, soil depth, organic matter, and soil biota vary from field to field and region to region and all have an effect on erosion and crop productivity. This is the reason that we carefully stated the conditions and assumptions for the assessments included in our tables 2 and 3.

Crosson indicates that the $27 billion on-farm economic costs that we estimated are too high. In his earlier paper (*13*), he estimated that the total annual cost of lost nutrients was $500 million for U.S. agriculture. This is in stark contrast to the $18 billion for 1980 (*14*) and $20 billion for 1991 (*8*) estimates of soil nutrient losses reported by several soil scientists at Iowa State University. In his letter, he has reduced the annual costs of nutrient and other erosion-caused losses to $100 to $120 million. Also, contrary to Crosson's models, a recent model study reports (*15*) that the annual economic costs of erosion on only 10 crops is a total of $2.1 billion, much greater than the $100 to $120 million for *all* crops, suggested by Crosson.

The major reason for differences between Crosson's and our assessment is that he generally relies on models to develop his results whereas we use data from field experiments of soil scientists for our assessment. Follet and Stewart (*16*) highlighted this type of controversy, and the results and conclusions between the two groups differed greatly. We believe that models are important, but feel confident that the results from models cannot substitute for data from field experiments.

We assessed the impact of erosion on reduced soil depth, loss of nutrients, loss of water, and on the important factors of soil organic matter and soil biota as well. The holistic assessment, we believe, provides a sound, realistic assessment of the environmental and economic costs of soil erosion.

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References

1. N. Myers, *Gaia: An Atlas of Planet Management* (Anchor and Doubleday, Garden City, NY 1993).
2. *The Second RCA Appraisal: Soil, Water, and Related Resources on Nonfederal Land in the United States* (U.S. Department of Agriculture, Washington, DC, 1989).
3. P. Buringh, in *Food and Natural Resources*, D. Pimentel and C. W. Hall, Eds. (Academic Press, San Diego, CA, 1989), pp. 69–83.
4. D. Pimentel, Ed., *World Soil Erosion and Conservation* (Cambridge Univ. Press, Cambridge, UK, 1993).
5. R. Lal, G. F. Hall, F. P. Miller, *Land Degrad. Rehab.* **1**, 51 (1989).
6. J. G. Speth, *Towards an Effective and Operational International Convention on Desertification* (International Negotiating Committee, International Convention on Desertification, United Nations, New York, 1994).
7. H. H. Bennett, *Soil Conservation* (McGraw-Hill, New York, 1939).
8. F. R. Troeh, J. A. Hobbs, R. L. Donahue, *Soil and Water Conservation* (Prentice-Hall, Englewood Cliffs, NJ, 1991).
9. R. Lal, in *Soil Degradation*, R. Lal and B. A. Stewart, Eds. (Springer-Verlag, New York, 1990), pp. 129–172.
10. N. Myers, *Deforestation Rates in Tropical Forests and Their Climatic Implications* (Friends of the Earth, London, 1989).
11. *Summary Report 1992 National Resources Inventory* (Soil Conservation Service, U.S. Department of Agriculture, Washington, DC, 1994).
12. F. R. Troeh and L. M. Thompson, *Soils and Soil Fertility* (Oxford Univ. Press, New York, ed. 5, 1993).
13. P. Crosson, in *Erosion and Soil Productivity* (American Society of Agricultural Engineers, St. Joseph, MI, 1985), pp. 254–265.
14. F. R. Troeh, J. A. Hobbs, R. L. Donahue, *Soil and Water Conservation Productivity and Environmental Protection* (Prentice-Hall, Englewood Cliffs, NJ, 1980).
15. P. Faeth, *Growing Green: Enhancing the Economic and Environmental Performance of U.S. Agriculture* (World Resources Institute, Washington, DC, 1995).
16. R. F. Follett and B. A. Stewart, Eds., *Soil Erosion and Crop Productivity* (American Society of Agronomy and Crop Science Society of America, Madison, WI, 1985).

Corrections and Clarifications

In the Research News article "Extreme ultraviolet satellites open new view of the sky" by Donald Goldsmith (14 Apr., p. 202), astronomer Stuart Bowyer was incorrectly identified as the director of the University of California, Berkeley's Center for Extreme Ultraviolet Astronomy. Bowyer was the founding director of the center and was succeeded by Roger Malina, who became acting director in 1994 and is now director. Malina is, with Bowyer, a principal investigator of the National Aeronautics and Space Administration's *EUVE* (Extreme Ultraviolet Explorer) mission.