ARTICLES

Environmental and Economic Costs of Soil Erosion and Conservation Benefits

David Pimentel, C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri, R. Blair

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.

5126 Comstock Hall, College of Agriculture and Life Sciences, Cornell University, Ithaca, NY, 14853-0901, USA.

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."

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Prehistoric Extinctions of Pacific Island Birds: Biodiversity Meets Zooarchaeology

David W. Steadman

On tropical Pacific islands, a human-caused "biodiversity crisis" began thousands of years ago and has nearly run its course. Bones identified from archaeological sites show that most species of land birds and populations of seabirds on those islands were exterminated by prehistoric human activities. The loss of birdlife in the tropical Pacific may exceed 2000 species (a majority of which were species of flightless rails) and thus represents a 20 percent worldwide reduction in the number of species of birds. The current global extinction crisis therefore has historic precedent.

Human activities are causing major changes in the Earth's biota (*1*). Extinction, the ultimate change, is occurring today across a broad range of terrestrial and aquatic habitats (*2*). Although much of this "biodiversity crisis" is due to human impact during recent centuries or decades, few plant and animal communities were unaffected in preindustrial times (*3*). Nowhere is this seen more dramatically than on islands in the Pacific Ocean.

Nearly all islands in Melanesia, Micronesia, and Polynesia (Fig. 1) were inhabited by prehistoric peoples. Melanesia was occupied as far east as the Solomon Islands by 30,000 years before the present (B.P.) or earlier (*4*). Much later, about 3500 years B.P., humans arrived in West Polynesia and Micronesia, reaching virtually all of Oceania by 1000 years B.P. (*5*). Native birds vanished as colonists cleared forests, cultivated crops, and raised domesticated animals (*6*). Having evolved in the absence of mammalian predators, the birds undoubtedly were tame and easy for people to hunt (*7*).

The loss of birds on oceanic islands may entail extinction (global loss of a species), extirpation (loss of a species from an island or region, with one or more populations surviving elsewhere), or reduced population. Extinction and extirpation are long-term losses (*8*), not short-term departures of populations soon to be reestablished from elsewhere (*9*). All families of Pacific island birds have been affected. Land birds have suffered high levels of both extinction and extirpation, especially among species of rails, pigeons, doves, parrots, and passerines. Although seabird colonies (especially of shearwaters and petrels) have vanished from numerous islands, species of seabirds have undergone little extinction.

Island birds have been lost mainly to predation by humans and nonnative mammals (rats, dogs, and pigs) and because of the removal or alteration of indigenous forests through cutting, burning, and introduction of nonnative plants. The soil erosion caused by deforestation has eliminated nest sites for burrowing seabirds. Although the rate of extinction varied with ruggedness of terrain and size or permanence of the prehistoric human population, we have no evidence that the processes responsible for prehistoric extinctions (*10*) differed fundamentally from those that continue to deplete surviving species today (*11*). The differences are mainly technological (snares versus guns and stone adzes and fire versus chain saws and fire, for example).

On average, fewer species and numbers of seabirds now nest on tropical or subtropical (0 to 35°S latitude) than on temperate or subantarctic (above 35°S latitude) Pacific islands, with lower marine productivity in the tropics generally cited as the reason for the difference (*12*). Without prehistoric human impact there would be less difference. For example, the number of nesting species of seabirds has declined on Ua Huka (Marquesas) from more than 22 to 4 (*13*) and on Huahine (Society Islands) from more than 15 to 4 (*14*). Today's global patterns of seabird distribution are not natural.

Remote Outposts: Hawai'i, New Zealand, and Easter Island

The highly endemic land bird faunas of the Hawaiian Islands and New Zealand evolved independently from those in the Polynesian heartland—the island groups from Tonga and Samoa to the Marquesas Islands that are the primary focus of this article. The prehistoric record of birds is extensive and well studied in the Hawaiian Islands (*15*, *16*) and New Zealand (*17*). As elsewhere in Polynesia, both seabirds and land birds were lost, with the land birds sustaining much more species-level extinction.

The Hawaiian Islands are renowned for radiations of endemic drepanidine finches and flightless ducks, geese, and ibises. Since human arrival at about 1500 to 2000 years B.P. (*18*), 60 endemic species (representing at least 90 populations) of land birds known only from bones have become extinct (Table 1). Another 20 to 25 species have been lost in the past two centuries. The large island of Hawai'i has the archipelago's richest modern avifauna, although more species are known from O'ahu and Maui because of their richer fossil records.

Temperate New Zealand once featured endemic radiations of moas, kiwis, water-

The author is at the New York State Museum, 3140 Cultural Education Center, Albany, NY 12230, USA.