World Agriculture and Soil Erosion

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Erosion threatens world food production

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Adequate food supplies depend on productive land. Soil erosion is a major environmental problem that threatens world food production (UNEP 1980). Today the human population is greater than ever before, and more people are malnourished (Swaminathan 1983). At present, one billion people are malnourished and the problem is growing rapidly (Latham 1984). Currently 97% of the world's food supply comes from land rather than oceans and other aquatic systems (CEQ 1980). Therefore, the control of soil erosion for a sustainable agricultural system is essential to any program to improve world food security and development.

Just at a time when agricultural efforts are focused on increasing crop yields, land degradation is increasing. The dimensions of land destruction are alarming; it affects about 35% of the earth's land surface (Mabbutt 1984). In some areas the productivity of eroded soils cannot be restored, even with heavy application of fertilizers and other inputs (Lal 1984a).

In this article, we address the relationship of soil erosion to the world food economy. We analyze patterns of soil degradation; the influence of soil erosion on food production; off-site environmental consequences of erosion; erosion-control measures for protecting agricultural land; economic factors that affect erosion; and soil and water conservation policies to control soil erosion and sustain agricultural systems.

The dimensions of land destruction are alarming

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Agricultural land degradation

The degradation of soil by erosion is of particular concern because soil reformation is extremely slow. Under tropical and temperate agricultural conditions, 200 to 1000 years are required for the formation of a 2.5 cm depth or 340 t/ha of topsoil (Elwell 1985, Hudson 1981, Lal 1984a, b).[1] This renewal rate is the equivalent of 0.3 to 2 t/ha/yr.

Serious soil erosion is occurring in most of the world's major agricultural regions (Table 1), and the problem is growing as more marginal land is brought into production. Soil loss rates, generally ranging from 10 to 100 t/ha/yr on cultivated lands, are exceeding soil formation rates by at least tenfold. Data compiled by Posner (1981) indicate especially severe soil losses on slopes in Latin America. In the United States soil erosion averages 18 t/ha/yr (OTA 1982).

[1]T. W. Scott, 1985, personal communication. Department of Agronomy, Cornell University, Ithaca, NY.

Worldwide degradation of agricultural land by erosion, salinization, and waterlogging is causing the irretrievable loss of an estimated 6 million hectares each year (UNEP 1980). More than half of the estimated 11.6 million hectares of forests cleared annually (FAO 1982) can be attributed to replacement of degraded agricultural soil (Pimentel et al. 1986a). Forest removal reduces fuelwood supplies and forces the poor in developing countries to rely more heavily on crop residues and manure for fuel. This diversion of crop residues and manure further intensifies soil erosion and water runoff and consumes valuable nutrients.

In addition, crop productivity on about 20 million hectares is approaching a negative net economic return due to land degradation (UNEP 1980). Agricultural land also is being lost to urban areas and roadways. For example, from 1945 to 1975 in the United States an area of agricultural land the size of Nebraska was blacktopped (Pimentel et al. 1976).

Erosion affects crop production

Erosion adversely affects crop productivity by reducing the availability of water, nutrients, and organic matter, and, as the topsoil thins, by restricting rooting depth (OTA 1982). Based on current worldwide soil loss, and projections for the period from

Table 1. Selected erosion rates in certain geographical regions. Source: Pimentel et al. 1986b.

Country	Erosion rate t/ha/yr	Comments
United States	18.1*	Average, all cropland
Midwest deep loesshills IA and MO	35.6*	MLRA† #107, 2.2 million ha
Southern high plains, KS, NM, OK, and TX	51.5*	MLRA† #77, 6.2 million ha
China	43	Average, all cultivated land
Yellow River Basin	100	Middle reaches, cultivated rolling loess soils
India		
	25–30	Cultivated land‡
	28–31	Cultivated land
Deccan black soil region	40–100	
Java	43.4	Brantas river basin
Belgium	10–25	Central Belgium, agricultural loess soils
East Germany	13	1000-year average, cultivated loess soils in one region
Ethiopia	20	Simien mountains, Gondor region
Madagascar	25–40	Nationwide average
Nigeria	14.4	Imo region, includes uncultivated land
El Salvador	19–190	Acelhuate Basin, land under basic grains production
Guatemala	200–3600	Corn production in mountain region
Thailand	21	Chao River Basin
Burma	139	Irrawaddy River Basin
Venezuela and Colombia	18	Orinoco River Basin

*Indicates combined wind and water erosion, all others are water only.
†MLRA = Major Land Resource Areas.
‡Assumes that 60–70% of the 6 billion tons of topsoil is lost from cultivated land.

1975 to 2000, degradation of arable land will depress food production between 15 to 30% (Shah et al. 1985).

Reduction in the water available to plants is erosion's most harmful effect (Follett and Stewart 1985). Both water and wind erosion reduce the water-holding capacity of soil by selectively removing organic matter and finer soil particles (Buntley and Bell 1976). In an investigation of a broad range of soil types and textures in the midwestern United States, water infiltration was most closely correlated with soil organic matter content (Wischmeier and Mannering 1965). In soils degraded by erosion, water infiltration may be reduced as much as 93% (Lal 1976). In Zimbabwe, there is 20 to 30% greater runoff of rainfall than under non-eroded conditions. This runoff results in water shortages even in years with good rainfall (Elwell 1985).

Water shortages severely affect crops at most stages of development. Water deficits reduce seed germination, seedling emergence, photosynthesis, respiration, leaf number and size, seed number, and seed filling (Jordan 1983). The photosynthetically active leaf area is an important factor in crop productivity, and it is also the component of growth that is the most sensitive to water stress (Jordan 1983).

Water stress also limits metabolism in crops. In leguminous crops, nitrogen fixation is much lower in stressed than unstressed nodules (Pankhurst and Sprent 1975). Water-stressed nonlegumes show a decreased capacity to convert soil nitrogen to metabolically usable forms (Hanson and Hitz 1983). Several major crops, such as corn, wheat, beans, rice, and potatoes, are among the most sensitive to water stress, with rice and corn suffering the greatest yield losses.

After water, shortages of soil nutrients (nitrogen, phosphorus, potassium, and calcium) are the most important factors limiting crop productivity. One ton of rich agricultural topsoil may contain a total of 4 kg of nitrogen; 1 kg of phosphorus; 20 kg of potassium; and 2 kg of calcium (Alexander 1977); however, only a small portion of these would be immediately available to the crop—18% of nitrogen and about 2% of the others (Larson et al. 1983). The US Department of Agriculture (USDA) estimates that about half of the 45 million tons of fertilizer (USDA 1985) applied annually in the United States are replacing the soil nutrients lost by erosion.

Erosion removes organic matter from soil; the material removed is commonly from 1.3 to 5 times richer in organic material than the soil left behind (Allison 1973). Organic matter is important to water retention, soil structure, and cation exchange capacity and is also the source of a large portion of the nutrients needed by plants. Ninety-five percent of the nitrogen in the surface soil and 15–80% of the phosphorus is found in organic matter (Allison 1973). Reducing the amount of soil organic matter by half lowers the yield of corn about 25% (Lucas et al. 1977). Conversely, increasing organic matter by annual application of animal or leguminous manure increases yields of wheat, sugar beets, and potatoes beyond those achieved with inorganic fertilizers—no matter how much additional nitrogen was added (Johnston and Mattingly 1976).

Organic matter is necessary to the formation of soil aggregates of desirable size, porosity, and stability (Chaney and Swift 1984). Good soil structure promotes root growth and helps the plant to obtain nutrients (Allison 1973). Therefore, when organic matter is lost by erosion both soil quality and crop productivity suffer.

Organic matter and soil biota are interrelated in maintaining soil quality and recycling nutrients. For example, earthworms and arthropods break up plant and animal residues, mix them into the soil, and make them available to microbes (Edwards and Lofty 1977). Then microbes break down this organic matter, making nutrients available to plants and producing stable humus (Alexander 1977, Allison 1973, Jenkinson and Ladd 1981). Substantial losses of organic matter limit populations of soil biota ranging from microbes to earthworms in the remaining soil and result in decreased soil quality, both in nutrient content and structure (Alexander 1977, Edwards and Lofty 1977).

Confusion exists over the effects of erosion, because the reduced crop productivity is caused by a complex set of ecological factors including water, nutrients, organic matter, soil biota, and soil depth (Follett and Stewart 1985). For instance, most economists estimate decreased productivity by observing the reduced soil depth. According to these assessments, the annual effect of soil erosion is a 0.1 to 0.5% reduction in productivity (Crosson 1985, Walker and Young 1986). However, when total erosion effects are measured, they range from 15 to 30% (Battiston et al. 1985, Schertz et al. 1985). Thus, although reduced soil depth is cumulative, the other factors, including loss of water, nutrients, and organic matter have a greater immediate impact on productivity.

Offsite environmental effects

In addition to reducing the productivity of the land, erosion and water runoff cause offsite environmental effects. Runoff in the United States delivers approximately 3 billion tons of sediment each year to waterways in the 48 contiguous states (NAS 1974). About 60% of these sediments come from agricultural lands (Highfill and Kimberlin 1977), and they frequently have detrimental effects on industry, agriculture, and wildlife. The offsite effects of erosion sediments in the United States cost an estimated $6 billion annually, including $570 million for dredging several million cubic meters of sediments from US rivers, harbors, and reservoirs. Another cost is the reduction in the useful life of reservoirs. An estimated 10 to 25% of new storage capacity in the United States is "currently built solely to store sediment" (Clark 1985).

Offsite effects of sediments are equally serious in other regions of the world. For example, the Archicaya Dam of Colombia was one-fourth filled with sediments after only 21 months and three-fourths filled after 10 years of use (UNEP 1982). A survey of 132 dams constructed 30–50 years ago in Masvingo, Zimbabwe, indicated over half were more than 50% filled with silt (Elwell 1985). Siltation of dam sites in India is reducing the capacity of reservoirs for irrigation, electricity, and flood control (CSE 1982).

When soil sediments that include pesticides from agricultural lands are carried into rivers, lakes, and reservoirs, fish production is adversely affected (USDI 1982). Sediments interfere with fish spawning, increase predation on fish, and destroy fish food (NAS 1982). These sediments can also destroy fisheries in estuarine and coastal areas (Day and Grindley 1981). In US streams, soil erosion damage to fish and other wildlife, water storage facilities, and navigation has been estimated to be about $4.1 billion each year (Clark 1985).

Contrary to popular belief, deposits of sediment left by floods do not necessarily enhance the productivity of lowland agricultural lands. In the United States, where lowland soils already are highly productive and usually are more fertile than sediment transported from less productive areas, deposited sediments cause about a ten-percent decline in productivity on flood plains across the country (Clark 1985).

Rapid water runoff floods poorly managed agricultural lowlands. In India, for example, during the last decade increased erosion and water runoff has more than doubled the amount of valuable cropland that is flooded, and annual flood damages in these areas range from $140 to $170 million (CSE 1982). In the United States, crop losses from flooding and thunderstorm activity reached $3.8 billion in 1982 and average at least $1 billion annually (USDC 1983).

When water is not held in soils but runs off quickly, the total soil moisture is diminished for crop and forages. As many as 80 nations, accounting for nearly 40% of the world population, experience frequent droughts (Kovda et al. 1978). With projected water needs expected to almost double in the next 20 years, water supplies emerge as a crucial aspect of crop production.

Erosion control technologies

The principal method of controlling soil erosion and its accompanying rapid water runoff is maintenance of adequate vegetative cover. Plants intercept and dissipate the energy in raindrops, enabling the water to reach the soil without damage. Further, plant stems, roots, and organic matter help control runoff and encourage water percolation into the soil. For example, water runoff rates have been measured to be as much as 10- to 102-fold greater on cleared land than on land covered with vegetation (Pimentel et al. 1986b). Greater water retention provides more water to sustain plant growth (Wischmeier and Smith 1978).

A variety of conservation technologies are effective in preventing or slowing soil erosion (Table 2). For example, in the Philippines, farmers have constructed terraces on slopes greater than 50% (equivalent to a 50 m decline per 100 m), and successfully cultivated irrigated paddy rice for several centuries without erosion problems (Conklin 1980). Terraces also have been shown to be an effective control measure for rainfed crops (Hurni and Nuntapong 1983). Many soil conservation technologies can be combined to reduce erosion rates about 1000-fold (IITA 1973). To determine the best combination of appropriate technologies, the soil, slope, locale, and available water must all be considered.

Causes of land degradation

Although many effective erosion control technologies are available, soil erosion persists at levels greatly in excess of soil formation rates in most major agricultural regions. This discrepancy is due to both characteristics of agricultural technology and the behavior of human populations.

The most fundamental cause of land degradation is the clearing and planting of land to feed the growing population. Because most of the world's fertile, arable land is already under production, most of the land newly placed under cultivation is only marginally productive (Buringh 1984). The newly planted land may be on fairly steep hillsides or contain relatively poor soils. For instance, in many Third World countries, such as the Philippines and Costa Rica, inequitable land tenure forces small family farms onto steep, easily eroded hillsides (UNEP 1982). Similar pat-

Table 2. Erosion control technologies examples. Source: Pimentel et al. 1986b and Krummel.*

Technology	Treatment	Soil loss (t/ha/yr)	Slope (%)	Country
Rotation	Corn-wheat-hay-hay-hay-hay	3	12	US
	Continuous corn	44	12	US
Contour planting	Potatoes on contour	0.2		US
	Potatoes, up-and-down hill	32		US
Rotation plus contour planting	Cotton on contour and grass strips	8		US
	Continuous cotton planted up-and-down hill	200		US
Terraces	Peppers on terraces	1.4	35	Malaysia
	Peppers on slope	63	35	Malaysia
Manure	Corn with 36 t/ha of wet manure	11	9	US
	Corn without manure	49	9	US
Mulch	Corn planted on land with 6 t/ha of rice straw	0.1	5	Nigeria
	Continuous corn	148	5	Nigeria
Grass cover	Grass	0.08	10	Tanzania
	Plowed	13.6	10	Tanzania
No-till	Corn	0.14	15	Nigeria
	Conventional corn	24	15	Nigeria
Ridge planting—crop residues left in trenches on land surface	Corn	0.2	2	US
	Conventional corn	10	2	US

*J. Krummel, 1985, personal communication. Oak Ridge National Laboratory, Oak Ridge, TN.

terns are found in more developed nations, such as the United States (Lee 1980).

Erosion increases dramatically on steep, unprotected cropland. For example, in Nigeria when cassava was planted on land with only a one-percent slope, the soil erosion rate was 3 t/ha/yr (Aina et al. 1977). However, on 5% and 15% slopes, erosion rates increased to 87 t/ha/yr and 221 t/ha/yr, respectively. The fact that such land is typically farmed by small landholders compounds this problem. Because these farmers need immediate cash or food returns, marginal lands are farmed more intensively than larger operations. Also, fragmented land ownership and the farmers' problems obtaining credit make conservation measures impractical (Hudson 1982).

In the post-World War II period, US agricultural structure has dramatically shifted toward fewer and larger farms, greater mechanization, and greater farm and regional specialization (USDA 1981). These large farms tend to use heavier, more powerful machinery (OTA 1982). Former terraces, shelter belts, and hedgerows have been removed because they restrict the operation of large machinery. Since large machinery is unable to follow contours on sloping cropland, contour planting has been modified. These changes all have intensified soil erosion (OTA 1982).

Farm and regional specialization also has contributed to soil loss. Most of the major food crops are row crops that require the soil to be tilled and planted each season. The exposure of freshly tilled soil to rain and wind facilitates erosion (Wischmeier and Smith 1978). Planting these crops with conventional tillage methods in larger and more continuous monocultures increases soil degradation by reducing crop rotations and crop diversity (see rotations in Table 2). The erosion potential of annual row crops is especially severe in the tropics because rainfall intensity is high (Elwell 1985, Lal 1984b).

On the level of farm economics, there are several constraints on soil conservation. Although the literature contains conflicting claims as to the private profitability of investment in erosion control technologies and practices, conditions of tenancy, debt, and inadequate income may preclude such investments even when they would otherwise be profitable. The latter problem is particularly relevant in the Third World nations where government policies often favor low producer prices (Brown et al. 1985).

Although the political, social, and human costs of reversing such policies may seem prohibitive, in the long term such adjustments will be necessary to encourage both increased food production and economic development (Brown et al. 1985). In the United States, for example, the economic benefits of conservation tillage have increased its use, so that it is now being practiced on nearly one-third of the cropland (Follett and Stewart 1985).

Finally, individual farmers often ignore erosion because of its insidious nature. The amount of soil that erodes with each rain or windstorm is almost imperceptible. For instance, 15 tons of soil lost from a hectare of land during a single storm removes only about 1 mm of soil from the surface.

Economics of land conservation

Implementing soil and water conservation technologies would benefit both farmers and society as a whole. For individual farmers, reducing erosion would help preserve the productivity of the land, reduce the need for fertilizers and other energy inputs, and decrease water stress on crop production.

In several experimental studies, conservation techniques allow the soil to retain about 10 cm more water per hectare (1 million liters/ha) per growing season than do conventional plow-plant technologies (Pimentel et al. 1986b). Application of five cm of water per hectare to corn, spring wheat, and sorghum crops, which normally experience transient drought periods during the growing season, has been calculated to increase average yields 15%, 25%, and 23%, respectively (de Wit 1958, Hanks 1983, Shalhevet et al. 1979). These calculations assume that the water lost in conventional tillage systems would be fully used by crops grown under conservation tillage systems. The calculated cost of replacing 5 cm of water by pumping ground water for irrigation averages about $15/ha/yr in the United States (USDA 1981).

Conserving soil nutrients is also important for crop production. Erosion (Larson et al. 1983) and water runoff (Lal 1976) annually reduce the available nutrients by 8.2 million tons of nitrogen, 0.06 million tons of phosphorus, and 2.0 million tons of potassium. At current fertilizer prices (nitrogen = 53¢/kg; phosphorus = 51¢/kg; potassium = 27¢/kg), the lost nutrients are worth nearly $5 billion. Other estimates of fertilizer nutrient losses range from $7 to $18 billion annually (Troeh et al. 1980). Retention of these nutrients through conservation technologies would substantially reduce US fertilizer costs, now about $10 billion annually (USDA 1985).

Conservation technologies to retain water, nutrients, and soil organic matter increase crop yields. For example, in Texas, yields from cotton grown on the contour were 25% greater than from cotton grown with the slope (Burnett and Fisher 1954). Yield increases from planting on the contour have also been reported for corn (12.5%) in Missouri (Smith 1946), and for corn (12%), soybeans (13%), and wheat (17%) in Illinois (Sauer and Case 1954). On land with a 7% slope, yields from cotton grown in rotation were increased 30%, while erosion was reduced nearly 50% (Hendrickson et al. 1963).

In Nigeria, yields from maize grown by no-till methods under favorable soil and climatic conditions were 61% greater than from corn grown with conventional tillage (Wijewardene and Waidyanatha 1984). In an experiment comparing tillage practices used on 22 consecutive maize crops grown on highly erodible Nigerian soils, the average grain yields from no-till plots were 20% higher than from conventionally tilled plots. This difference was attributed to the accumulated effects of erosion-induced degradation of the unprotected soil.

Assuming a minimum of ten percent reduced annual crop yield[2] and fertilizer loss of $5 billion, the short-term, onsite costs of erosion total $18 billion annually in the United States. The long-term losses are much greater. For example, when an average erosion rate of 18 t/ha/yr occurs for ten years, about 1.3 cm of soil is lost. This decreased soil depth would reduce corn yields about eight percent on soils less than 30 cm in depth, and is equivalent to a loss of 520 kg corn/ha/yr. Assuming this reduced yield can be offset by fertilizer and other production inputs, then about $20/ha/yr is required to offset reduced soil depth (478,000 kcal required for the 520 kg reduced yield).

Replacing this 1.3 cm of topsoil would require 110 to 400 years. Therefore, even if conservation measures are adopted after the tenth year, added fertilizer and other inputs would have to be applied for more than a century to maintain the original productivity of the land. Wasting a renewable soil resource that requires hundreds of years to replace and substituting a nonrenewable resource is economically and environmentally unsound.

The offsite environmental costs of erosion—the sediment and flood effects—are estimated at an additional $6 billion annually in the United States (Clark 1985). Thus, the total short-term cost of both onsite and offsite environmental effects of US soil erosion and water runoff is estimated at about $24 billion annually.

[2]Conventional production results in erosion and water runoff and yield reductions from 12 to 61% compared to conservation technologies.

Conclusion

Severe soil erosion and rapid water runoff problems are a crisis that is seriously affecting the world food economy. High rates of soil loss are causing declines in soil productivity worldwide, and most nations do not have sound land-use policies to protect their soil and water resources. In fact, low-cost food policies by most governments encourage farmers to use poor management practices in agriculture.

Because of the insidious nature of soil erosion and the complexity of environmental effects, few measurements have been made of the total costs of erosion and water runoff to farmers and society as a whole. We find that soil erosion and associated water runoff cost the United States about $43.5 billion annually in direct and indirect effects. The long-term environmental and social costs may be several times this level. Clearly, it would pay society to invest in soil and water conservation.

The demand for food for the growing population is placing increasing pressure on limited cropland and water resources. Poverty and inequity in some nations is forcing subsistence farmers to expand their cultivation onto erosion-prone marginal lands. The limited availability of fossil energy resources and their cost, which is expected to increase, make it unlikely that fertilizers and other inputs can offset severe land and water degradation problems, especially in impoverished nations.

The results of our assessment not only underscore the serious nature of the environmental and social costs of soil erosion worldwide, but emphasize the need for immediate implementation of soil erosion control technologies. Sound soil and water resource management policies would be a substantial benefit to all nations now and in the future.

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