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*BioScience*, Vol. 47, No. 11. (Dec., 1997), pp. 747-757.

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# Economic and Environmental Benefits of Biodiversity

*The annual economic and environmental benefits of biodiversity in the United States total approximately \$300 billion*

David Pimentel, Christa Wilson, Christine McCullum, Rachel Huang, Paulette Dwen, Jessica Flack, Quynh Tran, Tamara Saltman, and Barbara Cliff

All ecosystems and human societies depend on a healthy and productive natural environment that contains diverse plant and animal species. The earth's biota is composed of an estimated 10 million species of plants, animals, and microbes (Pimm et al. 1995). In the United States, there are an estimated 750,000 species, of which small organisms, such as arthropods and microbes, make up 95%.<sup>1</sup> Although approximately 60% of the world's food supply comes from rice, wheat, and corn (Wilson 1988), as many as 20,000 other plant species have been used by humans as food. Some plants and animals provide humans with essential medicines and other diverse, useful products. For instance, some plants and microbes help to degrade chemical pollutants and organic wastes and recycle nutrients throughout the ecosystem.

The rapidly growing world population and increased human activity threaten many of these species. The current extinction rate of species ranges from approximately 1000 to 10,000 times higher than natural extinction rates (Kellert and Wilson

David Pimentel (e-mail: dp18@cornell.edu) is a professor in the College of Agriculture and Life Sciences at Cornell University, Ithaca, NY 14853-0901. Christa Wilson, Christine McCullum, Rachel Huang, Paulette Dwen, Jessica Flack, Quynh Tran, Tamara Saltman, and Barbara Cliff are graduate students in the College of Agriculture and Life Sciences at Cornell University, Ithaca, NY 14853-0901. © 1997 American Institute of Biological Sciences.

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## Some aspects of conserving biodiversity are expensive, although they may return major dividends

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1993), and if this trend continues, as many as 2 million species of plants and animals will be exterminated worldwide by the middle of the next century (Pimm et al. 1995). This forecast is alarming because biodiversity is essential for the sustainable functioning of the agricultural, forest, and natural ecosystems on which humans depend (Myers 1994, Raven and Johnson 1992, Wilson 1994). For example, the loss of a key species (e.g., a pollinator) can cause the collapse of an ecosystem (Heywood 1995).

When humans cause extinctions or pollute or deplete resources on which biological services are based, contributions from biodiversity are jeopardized. For example, although the United States spends \$150 billion each year to clean polluted water, air, and soil (Allen 1996), 40% of the lakes in the United States are unfit for swimming and other uses (Zimmer 1996). This pollution not only threatens public health, but also reduces aquatic biodiversity.

In this article, we analyze the vital services that are provided by all biota

(biodiversity), including their genes and biomass, to humans and to the environment. We assess the economic and environmental benefits of the following major contributions of biodiversity: organic waste disposal, soil formation, biological nitrogen fixation, crop and livestock genetics, biological pest control, plant pollination, and pharmaceuticals. Such an assessment can serve as a foundation to develop strategies and policies to preserve biological diversity and maintain ecosystem integrity.

## Biomass and the recycling of organic wastes

Humans, other animals, and microbes depend on plants to collect solar energy and to produce and store essential biomass and nutrients. Including managed agricultural and forestry biomass production, more than 50% of total photosynthetic production on land is used by humans.<sup>2</sup>

To produce enough animal food products for the growing world population, approximately 20 billion domestic animals are maintained worldwide, 9 billion of which are raised in the United States (Table 1; Agrostat 1992, USBC 1995, USDA 1995). The biomass of domestic animals in the United States totals 4.5 times that of the human population. Worldwide, domestic animals outweigh the human population by 2.5 times (Table 1). Nearly one-third of the world's

<sup>1</sup>P. H. Raven, 1996, personal communication. Missouri Botanical Garden, St. Louis, MO.

<sup>2</sup>D. Pimentel, C. Wilson, C. McCullum, R. Huang, P. Dwen, J. Flack, Q. Tran, T. Saltman, B. Cliff, unpublished manuscript.

**Table 1.** Total number and biomass of humans, domestic animals, crops, and wastes.

Group	Number ( $\times 10^9$ )	Biomass (wet) ( $\times 10^9$ kg)	Wastes (wet) <sup>a</sup> ( $\times 10^9$ t)
Humans			
United States	0.26 <sup>b</sup>	18.4 <sup>a</sup>	0.26
World	6 <sup>c</sup>	420 <sup>a</sup>	6
Domestic animals			
United States	9 <sup>d</sup>	90 <sup>a</sup>	1.1
World	20 <sup>e</sup>	1000 <sup>a</sup>	14
Crops			
United States	—	3000 <sup>f</sup>	1.7
World	—	30,000 <sup>f</sup>	15
Total			38.06

<sup>a</sup>Estimated based on the average weight of a human and average weight of a domestic animal.

<sup>b</sup>USBC 1994

<sup>c</sup>PRB 1995

<sup>d</sup>USDA 1993 (Two-thirds poultry)

<sup>e</sup>Agrostat 1992 (Two-thirds poultry)

<sup>f</sup>Estimated based on the average weight of crops per hectare and the number of hectares in production in the United States and the world.

land area and one-half of US land is used to grow wild and cultivated plants that are fed to domestic animals.

Each year, humans, livestock, and crops produce approximately 38 billion metric tons of organic wastes worldwide. These wastes are recycled by a variety of decomposer organisms (Table 1). We estimate the economic benefit of these waste disposal activities to be \$0.02/kg, based on the information that it costs \$0.04–0.044/kg to collect and dispose of organic wastes that are produced in the Village of Cayuga Heights, New York, or in the city of Madison, Wisconsin (Einstein 1995). Assuming a conservative value of \$0.02/kg for all organic wastes that

are recycled by decomposers, the contribution made by decomposer organisms is worth more than \$62 billion per year in the United States (where 3.1 billion tons of organic waste is recycled) and more than \$760 billion per year worldwide (Table 2 and Figure 1). This calculation does not take into account the benefits of decreased environmental pollution, the recycling of nutrients, the decrease in the need for landfills, and the significant reduction in human diseases.

### Biodiversity and soil formation

Fertile soil is an essential component of the world's ecosystems because all plant and animal species need either

soil or products that are grown in soil for their survival. More than 99% of the total worldwide human food supply is produced on land, whereas only 0.6% comes from oceans and other aquatic ecosystems (FAO 1991).

Diverse soil biota facilitate soil formation and improve it for crop production. One square meter of soil frequently supports populations of approximately 200,000 arthropods and enchytraeids and billions of microbes (Pimentel et al. 1995). One hectare of high-quality soil contains an average of 1300 kg of earthworms, 1000 kg of arthropods, 3000 kg of bacteria, 4000 kg of fungi, and many other plants and animals (Pimentel et al. 1992).

Earthworms bring between 10 and 500 t · ha<sup>-1</sup> · yr<sup>-1</sup> of soil to the surface (Pimentel et al. 1995), whereas insects often bring between 1 and 10 t · ha<sup>-1</sup> · yr<sup>-1</sup> of soil to the surface (Pimentel et al. 1995). Earthworms may ingest as much as 500 t · ha<sup>-1</sup> · yr<sup>-1</sup> of soil, thereby churning and mixing the soil (Pimentel et al. 1995). Similarly, organisms like the desert snail *Trochoidea seetzenii* help to form approximately 1000 kg · ha<sup>-1</sup> · yr<sup>-1</sup> of soil, an amount that is equivalent to the annual rate of soil formation by wind-borne dust deposits (Shachak et al. 1995). These combined activities of snails, earthworms, and other organisms redistribute nutrients, aerate the soil, facilitate topsoil formation, and increase rates of water infiltration, thereby enhancing plant productivity (Pimentel et al. 1995).

Despite the activities of soil biota and the mechanical mixing of soil by agricultural machinery, soil formation on cropland is slow. It is even slower under natural forest and grassland conditions. For example, under agricultural conditions it takes approximately 500 years to form 25 mm of soil, whereas under forest conditions it takes approximately 1000 years to form the same amount of soil (Pimentel et al. 1995).

Because earthworms and other invertebrate species bring between 10 and 500 t · ha<sup>-1</sup> · yr<sup>-1</sup> of subsurface soil to the surface, we estimate that the presence of soil biota aids the formation of approximately 1 t · ha<sup>-1</sup> · yr<sup>-1</sup> of topsoil (Pimentel et al. 1995).

**Table 2.** Total estimated economic benefits of biodiversity in the United States and worldwide (see text for details).

Activity	United States ( $\times \$10^9$ )	World ( $\times \$10^9$ )
Waste disposal	62	760
Soil formation	5	25
Nitrogen fixation	8	90
Bioremediation of chemicals	22.5	121
Crop breeding (genetics)	20	115
Livestock breeding (genetics)	20	40
Biotechnology	2.5	6
Biocontrol of pests (crops)	12	100
Biocontrol of pests (forests)	5	60
Host plant resistance (crops)	8	80
Host plant resistance (forests)	0.8	11
Perennial grains (potential)	17	170
Pollination	40	200
Fishing	29	60
Hunting	12	25
Seafood	2.5	82
Other wild foods	0.5	180
Wood products	8	84
Ecotourism	18	500
Pharmaceuticals from plants	20	84
Forests sequestering of carbon dioxide	6	135
Total	\$319	\$2928

Using this assumption, and a value to agriculture of approximately \$12 per ton of topsoil (Pimentel et al. 1995), a conservative total value of soil biota activity to soil formation on US agricultural land (approximately 400 million hectares) is approximately \$5 billion per year (Table 2). For the 4.5 billion hectares of world agricultural land, soil biota contribute approximately \$25 billion per year in topsoil value (Table 2).

## Nitrogen fixation

Nitrogen is essential for plant growth, and an insufficient quantity of it frequently limits biomass production in both natural and agricultural ecosystems. More than 77 million tons of commercial nitrogen is used in world agriculture each year, at a cost of approximately \$38.5 billion (USDA 1995). Soil nitrogen is increased not only by commercial fertilizers but also by the addition of animal wastes and the retention of crop residues. However, some of the best sources of nitrogen for crop and other plants are nitrogen-fixing plants and obligate endophytic diazotroph bacteria (Dobereiner 1995).

Biological nitrogen fixation is a process in which atmospheric  $N_2$  is converted into substrates of nitrogen that plants can use (Dobereiner et al. 1995). Biological nitrogen fixation in the United States yields approximately  $14 \times 10^6$  t/yr of usable nitrogen, with a value of \$8 billion (Table 2; Bezdicsek and Kennedy 1988). This fixed nitrogen is equal to approximately half of the commercial nitrogen fertilizer applied to US farmland every year (USBC 1995). Worldwide,  $140\text{--}170 \times 10^6$  t/yr of nitrogen, valued at approximately \$90 billion, is fixed by many microorganisms in both agricultural and natural ecosystems (Table 2 and Figure 1; Bezdicsek and Kennedy 1988, Peoples and Craswell 1992).

Nitrogen fixation in leguminous plants is dominated by a variety of endosymbiotic bacteria. This process fixes an average of  $80 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$  of nitrogen worldwide. In addition, recent discoveries indicate that obligate endophytic diazotroph bacteria add as much as  $150 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$  of nitrogen to agricultural and natural ecosystems (Dobereiner 1995).

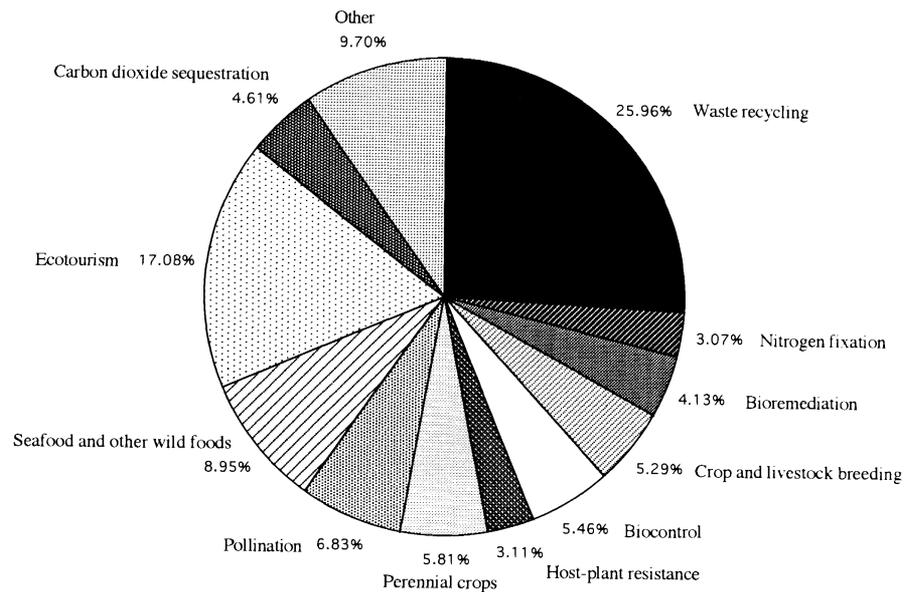


Figure 1. The proportion of economic benefits to world society from biodiversity.

Biological nitrogen fixation is the major alternative to the use of commercial nitrogen fertilizer in agriculture (Dobereiner and Pedrosa 1987). In the United States and other developed countries, approximately 30% of the fossil energy used in agriculture is associated with the production of nitrogen fertilizer (Pimentel 1980). As natural gas, coal, and oil supplies become increasingly scarce and more expensive, contributions from biological nitrogen fixation will become even more vital to the productivity of future agricultural systems.

## Bioremediation of chemical pollution

Advances in technology have resulted in the production of a wide range of chemicals, many of which have contributed to ecosystem pollution. Currently, some 70,000 different chemicals are used in the United States and released into the environment through soil, water, and air (Newton and Dillingham 1994); an estimated 100,000 chemicals are used worldwide (Nash 1993). Nearly 10% of the chemicals used in the United States are known carcinogens (Darnay 1994). In the United States, yearly chemical releases total over 290 billion kg (Montague 1989), or more than 1100 kg per person per year. Over the years, the accumulation of chemicals in the environment has

resulted in an estimated 400,000–600,000 hazardous waste sites just in the United States (Yount and Williams 1996) and countless more throughout the world.

Chemicals that are toxic to the environment or to humans must be removed. Removing chemicals from the environment (remediation) can be achieved by biological, physical, chemical, and thermal methods. Biological treatments, which use microbes and plants to degrade chemical materials, can both decontaminate polluted sites (bioremediation) and purify hazardous wastes in water (biotreatment). Overall, biological methods are more effective than physical, chemical, and thermal methods, because the latter methods often simply transfer the pollutant to a different medium instead of converting it to a less toxic substance, as biological methods often do. In addition, incineration of many chemicals produces dioxins, which are highly carcinogenic. Currently, approximately 75% (by weight) of the chemicals released into the environment can be degraded by biological organisms<sup>3</sup> and are potential targets of both bioremediation and biotreatment. The ability of bioremediation to provide continuous cleanup of contaminated sites, such as agricul-

<sup>3</sup>M. Carroquino, 1995, personal communication. Cornell University, Ithaca, NY.

tural ecosystems with toxic pesticide residues, is a significant advantage of this method. Furthermore, a significant degree of self-regulation is present in such biological systems because the added microbes survive by consuming and degrading chemicals but die when the nutrient source—that is, the pollutant—is reduced or eliminated.

Most chemicals are released primarily into the air and into water (Alexander 1994), but some chemicals are also released into the soil. Approximately 23% of all terrestrial ecosystems have been exposed to toxic chemicals (Tadesse et al. 1994). Nearly 80% of bioremediation efforts of the US Environmental Protection Agency now focus on eliminating soil pollution because most pollutants end up in soil and many organisms are present in the soil (EPA 1994a). Anderson (1978) reports that a favorable temperate forest soil may support up to 1000 species of animals per square meter, including arthropods, nematodes, and protozoa. Soil bacteria and fungi add another 4000–5000 species to the biodiversity of moist forest soil ecosystems (Heywood 1995). Combined, these diverse organisms facilitate the biological degradation of both point and nonpoint sources of soil pollutants.

Bioremediation is effective in cleaning up highly polluted soils. For example, an oil gasification plant in southern Ontario produced an oil-tar byproduct containing benzene, toluene, xylene, cyanide, heavy metals, polycyclic aromatic hydrocarbons, and phenols that contaminated an estimated 38,000 m<sup>3</sup> of soil (Warith et al. 1992). Application of a nitrogen nutrient and bacterial mixture reduced the various oil-tar pollutants by 40–90% after just 70–90 days of treatment (Warith et al. 1992).

The growing interest in bioremediation is due in large measure to its economic benefits. For example, if bioremediation had been used to clean up the entire Alaskan shoreline that was contaminated by the Exxon Valdez oil spill in 1989, the cleanup cost would have been less than \$0.25 billion rather than the \$2.5 billion actual cost (EPA 1995). This tenfold decrease in remediation costs is generally accepted as the standard when

comparing bioremediation with conventional methods such as thermal and physical remediation.

The US Geological Survey Toxic Substances Hydrology Program estimates a total cost of \$750 billion over the next 30 years to remediate all known hazardous waste sites. This estimate includes Superfund sites as well as other sites and federal facilities (USGS 1995). The use of bioremediation would reduce this cost to only \$75 billion over the same period, a savings of \$22.5 billion per year (Table 2). Considering that the United States produces the largest amount of chemical pollution, and assuming a proportion of the total amount that is similar to the ratio of US markets to world markets for environmental technology, the cost to remediate chemical pollution worldwide using current technologies is extrapolated to be \$135 billion per year. Using bioremediation, the cost would be approximately \$14 billion per year, providing benefits of \$121 billion per year (Table 2).

Maintaining biodiversity in soils and water is imperative to the continued and improved effectiveness of bioremediation and biotreatment. The presence of large numbers of microorganismal species expands both the variety of and extent to which chemical pollution in the environment can be degraded.

### **Genetic resources increase crop and livestock yields**

Approximately 250,000 plant species have been described worldwide (Raven and Johnson 1992). Many of these species provide valuable genetic material for some of the most important crop plants for humans. Since 1945, world crop yields have increased between two- and four-fold, depending on the crop. An estimated 20–40% of this increase has been achieved by genetic modification and breeding, which improved hybrid vigor and host plant resistance. Another 30–50% of the yield increase has resulted from increased fossil energy inputs such as commercial fertilizers (Babcock and Foster 1991). Cultural changes, such as doubling the density of crop plants per hectare, are responsible for an additional 10–50% increase in yield,

depending on the crop. The increases in annual crop yields since 1945 are worth approximately \$60 billion per year (USBC 1995). Assuming that the contribution of genetic resources is responsible for 30% of the yield increase, the introduction of new genes and genetic modifications through crossing with wild relatives contributes approximately \$20 billion per year in increased crop yields to the United States and an estimated \$115 billion per year worldwide (Table 2).

Classical plant breeding has increased yields for several crops, such as rice, wheat, and corn, that are important outside the United States. In Asia, for example, the estimated benefits of genetically improved rice and wheat total \$1.5 billion per year and \$20 billion per year, respectively (Oldfield 1984). A new strain of rice genetically improved through hybridization with other rice genotypes in Asia increased the value of this crop by \$1 billion within two years (Facklam and Facklam 1990). In the United States, the value of improved dwarf rice alone is estimated to have added more than \$2.5 billion to the agricultural economy over the last 25 years (Raeburn 1995).

Genetic resources have also increased production yields in the livestock industry, especially in dairy cattle, hogs, and poultry. For example, milk production per dairy cow was approximately 3600 kg/yr in 1935, but the yield is now approximately 8600 kg/yr (USDA 1995). Similarly, average yearly egg production per hen was only 93 eggs in 1930, and it has now risen to 246 eggs (Johnson 1995). Broiler chicken production has also increased dramatically. For instance, in 1930 approximately 13 kg of feed was required to produce 1 kg of broiler chicken, whereas only 1.9 kg of feed is needed today (Johnson 1995). These increases in efficiency have resulted from a combination of breeding technology and improved feed and husbandry (Johnson 1995).

The total increase in the value of US livestock production is approximately \$60 billion per year. Again assuming that one-third of the benefits are due to genetic breeding, the benefits from the use of biodiversity total at least \$20 billion per year

(Table 2); assuming a similar increase for livestock production worldwide, the estimated benefits are \$40 billion per year (Table 2 and Figure 1).

## Biotechnology

Advances in biotechnology have enabled the transfer of genetic traits both within species and between entirely different plant and animal species. Thus, such technologies have the potential to enhance and to accelerate the genetic modification of both crops and livestock, improving productivity, the development of new food and fiber crops, and pest control.

Biotechnological gene transfer is currently being used in various fields, including agriculture, forestry, veterinary and human medicine, pharmaceutical development, energy conservation, and waste treatment (BIO 1990). Potential environmental and economic benefits of biotechnology include the reduction of fossil fuel use in agriculture and forestry (i.e., if crops can be engineered to produce their own nutrients); the reduction of artificial inputs, such as fertilizer and insecticides (i.e., if crops can be engineered to fix their own nitrogen and produce their own insecticidal compounds); and more cost-effective and environmentally friendly waste management practices, such as bioremediation (i.e., if plants or microbes can be engineered to be better bioremediators).

For example, by using biotechnological approaches to transfer genes that allow legumes to form symbioses with nitrogen-fixing bacteria into nonlegume crops, such as wheat and corn, these crops may gain the ability to form these symbioses. Such an advance would significantly reduce the need for commercial nitrate fertilizers (Mannion 1995). However, because the molecular mechanisms that are required for symbiotic nitrogen fixation are complex—involving at least 17 genes in the plant—achieving this goal may require an investment in research over several decades.

Biotechnology approaches have been used successfully to incorporate a toxin gene from *Bacillus thuringiensis* (Bt) into cotton plants to control caterpillar pests, including the cotton bollworm and bud-

worm. These pests currently cost US farmers \$171 million per year in yield losses and insecticide costs (Head 1992). Benedict et al. (1992) predicted that the widespread use of Bt cotton could reduce these costs by as much as 50–90%, saving farmers between \$86 and \$154 million per year. Widespread pesticide use on cotton crops would also be greatly reduced.

The present economic benefits of biotechnology products are significant, conservatively estimated to be between \$2 and \$3 billion per year in the United States (Table 2; Kathuri et al. 1993). Worldwide, current benefits are approximately \$6.2 billion per year (Kathuri et al. 1993) and are projected to increase to \$9 billion per year by the turn of the century (Table 2; USDC 1984). Nearly half of the current economic benefits of biotechnology relate to agriculture, with significant benefits in the pharmaceutical industry (Kathuri et al. 1993).

## Biological pest control

Approximately 70,000 pest species attack agricultural crops throughout the world (Pimentel 1991a). Between 30% and 80% of the pests in any geographic region are native species. Thus, indigenous insects and pathogens have moved from feeding on native vegetation to becoming pests on introduced crops (Hokkanen and Pimentel 1989).

Approximately 99% of pests are controlled by natural enemy species and host plant resistance (DeBach and Rosen 1991). Each insect pest has an average of 10–15 natural enemies that help to control it (van den Bosch and Messenger 1973). However, some pests, such as the gypsy moth (*Lymantria dispar*), have as many as 100 natural enemies (Pimentel 1988). However, the value of these natural enemies to pest control is often overlooked.

Despite heavy pesticide application ( $0.5 \times 10^6$  t/yr) at an estimated cost of \$6 billion, plus various nonchemical controls, including natural enemies, US crop losses to pests are estimated to reach 37% per year (Pimentel et al. 1991). This loss is equivalent to an estimated \$50 billion per year loss in food and fiber

in the United States, despite all efforts to control these pests. On the positive side, pesticide applications reduce potential US crop losses by approximately \$20 billion per year, natural enemies reduce losses by approximately \$12 billion per year (Table 2), and host plant resistance and other nonchemical pest controls reduce losses by an additional estimated \$8 billion per year (Pimentel 1997). Thus, pest control benefits total at least \$40 billion per year. Without pesticides, natural enemies, host plant resistance, and other nonchemical controls, 67% of crops would be lost, at a cost of approximately \$90 billion per year (Pimentel 1997).

Worldwide, pests reduce the yields of major crops by approximately 42% each year, despite the application of an estimated  $2.5 \times 10^6$  t/yr of pesticides at a cost of \$26 billion, plus the benefits of various nonchemical controls (Oerke et al. 1994). The total cost of losses to pests is estimated to be \$244 billion per year. Without pesticides, natural enemies, host plant resistance, and other nonchemical controls, 70% of crops could be lost to pests (Oerke et al. 1994), increasing the cost of losses to approximately \$400 billion per year (Oerke et al. 1994). We estimate from field experience that natural enemies provide 60% of the benefits from nonchemical controls. Therefore, natural enemies provide approximately \$100 billion worth of pest control worldwide per year (Table 2 and Figure 1).

Natural enemy species also are effective in protecting forests from pests. For example, bird predation on insects is estimated to provide annual benefits in insect control equivalent to as much as \$180/ha in US spruce forests (Diamond 1987). All together, birds and all other natural enemies provide estimated annual benefits to forests of \$18/ha. Thus, a conservative estimate of the benefits provided by all natural enemies to US forests on approximately 270 million hectares is approximately \$5 billion per year. Extrapolating to world forests, which cover 14 times the area of US forests, the value of the protection to forests offered by natural enemies is estimated to be \$60 billion per year worldwide (Table 2).

## Host plant resistance and pest control

Host plant resistance, including characteristics such as hairs, hardness, nutrient changes, toxins, and repellents, is another major control method for insect and plant pathogen pests. Using resistant crop varieties in agriculture is economically and environmentally beneficial because such varieties significantly reduce the need for pesticides. For example, resistance genes have now been identified for all major cereal grain pathogens, reducing the need for the application of pesticides on these crops.

In the wild, all plant species exhibit some degree of natural host plant resistance, which protects them from many of their pests (Subramanian 1977). For instance, Hanover (1975) reported that there may be approximately 1000 chemicals in a single tree, yielding a multitude of potential combinations to provide for pest control. Through advances in plant breeding and biotechnology, such resistance genes are fairly quickly and easily transferred from wild to cultivated crops to improve crop resistance.

From 75% to 100% of agricultural crops contain some degree of host plant resistance (Oldfield 1984, Pimentel et al. 1989). These resistance traits improve yields and, thus, economic returns to growers. For example, when host plant resistance was integrated into a control program for potatoes, only half the normal amount of fungicide was needed to suppress early and late blights on potatoes (Shtienberg et al. 1994), a potential savings of approximately \$7 million per year in the United States (Pimentel et al. 1991). We estimate that in the United States, the presence of host plant resistance prevents 40% of the \$20 billion in potential losses to pest insects and pathogens, amounting to a savings of \$8 billion per year; worldwide savings are estimated to be approximately \$80 billion per year (Table 2).

Similarly, host plant resistance helps to control damage from insect pests and plant pathogens in forests. Host plant resistance is about as effective as natural enemies (Pimentel 1991a), so we estimate that each year, host plant resistance saves ap-

proximately \$3/ha by preventing insect and disease damage in forests (Pimentel 1988). Overall, the value of host plant resistance to forests is approximately \$800 million per year in the United States and approximately \$11 billion per year worldwide (Table 2 and Figure 1).

Pests frequently evolve tolerance to the resistance factors in crops (e.g., oat lines previously resistant to oat rust disease become susceptible to it). To overcome such tolerance, additional genetic diversity is needed. Genes from wild and cultivated plant species that are regularly exposed to endemic diseases and, thus, maintain new forms of resistance can then be transferred to crops by both traditional breeding and biotechnology (Harlan 1977).

## Perennial cereal grains

The dominant grain crops grown worldwide are rice, wheat, corn, millet, barley, and rye. In temperate zones, most grain crops are planted as annuals because they are not cold tolerant. Annual cropping is also used in the tropics as a way to deal with weeds, insects, and plant pathogens (Pimentel 1991b). Clearing wild vegetation by tillage eliminates many pest insects, plant pathogens, and weeds before planting an annual crop.

Cereal grains are produced on 70% of arable land worldwide; production totals approximately  $2 \times 10^9$  t/yr (USDA 1995). These grains provide 80% of the food that humans consume. Planting large areas to annual crops damages the immediate agroecosystem and beyond. For instance, the practice of spring and fall tilling leaves the soil exposed and makes it susceptible to water and wind erosion (Pimentel et al. 1995). In fact, US agricultural practices are responsible for 64% of the total pollution that is entering streams and 57% of the pollutants that are entering lakes through erosion (Miller 1992).

In contrast to annual grains, perennial grains can be grown and harvested continuously for a period of 4–5 years without tilling and replanting (Piper 1993). Soil erosion could be reduced by as much as 50% because soils are left relatively undisturbed and covered with vegetation (Moffat 1996).

The development of perennial grain crops could also reduce fuel consumption, by as much as 72% per hectare (Wagoner et al. 1993). If US corn were grown as a perennial, the savings in diesel fuel alone could reach \$300 million per year because the energy expended for sowing and frequent cultivation would be eliminated (Raeburn 1995).

Estimates of the economic benefits of perennial grain development can be based on potential reductions in soil erosion, fossil fuel use, and environmental pollution. Planting perennial grains could save approximately \$20 billion per year in reduced soil erosion (Pimentel et al. 1995) and \$9 billion per year in reduced tractor fuel inputs (Wagoner et al. 1993). In addition, there would be savings of at least \$1 billion per year in reduced agricultural and environmental pollution because pesticide and fertilizer use would be reduced (Pimentel and Greiner 1997). The potential economic benefits associated with the development and use of perennial grains in the United States could therefore total as much as \$17 billion per year (Table 2); worldwide, a perennial grain system could be worth as much as \$170 billion per year (Table 2 and Figure 1).

Although none of the major grain crops that are grown now are perennials worldwide, some perennial grain types have been identified in the wild. For example, a perennial corn species that is highly restricted in range and is infertile with cultivated corn was discovered in the Sierra de Manantlan Mountains in central Mexico approximately 20 years ago (Prescott-Allen and Prescott-Allen 1986). It is possible that this perennial corn genotype or another one that has been identified in South America might provide the basis for the eventual development of a perennial corn genotype. Achieving a commercial perennial corn, however, will be extremely difficult (Raeburn 1995). Perennial wheat and sorghum genotypes exist that could be the basis of perennial cropping of these grains as well (Wagoner 1990).

## Pollination

Pollinators, such as bees, butterflies, birds, and bats, provide substantial

benefits to the maintenance, diversity, and productivity of both agricultural and natural ecosystems (Buchmann and Nabhan 1996). As much as one-third of the world's food production relies either directly or indirectly on insect pollination (Richards 1993). Although many major crops are self- or wind pollinated, others require and benefit from insect pollination to increase quality or increase yields (Richards 1993). Even some self-pollinated domesticated crops, such as the banana, rely on animal-pollinated wild relatives to provide the genetic diversity that is essential for crop improvement (Fujita and Tuttle 1991).

Pollinator diversity depends on ecosystems that are rich in diverse vegetation (LaSalle and Gould 1993). Approximately 6000 species of native plants, or approximately one-third of the total species in the United States, are outcrossed via pollinators.<sup>4</sup> An estimated one-third of the world's plant species (Holsinger 1992) depend on biological cross-pollination. In US agriculture, approximately 130 crop species are insect pollinated (Southwick 1992).

Insects are the largest group of pollinators, with honeybees estimated to provide approximately 80% of all insect pollination (Robinson et al. 1989). In North America, approximately 4000 bee species have some ability to pollinate (Robinson et al. 1989, Southwick 1992). Worldwide, at least 20,000 species of bee pollinators have been described (O'Toole and Raw 1991).

Although most estimates of the economic value of pollination in agricultural systems focus on honeybees, honeybees frequently receive credit for pollination that is carried out by other bee species or other insects (Richards 1993). The value of pollination to US agricultural production is estimated to be \$40 billion per year when the value of insect-pollinated legumes fed to cattle is included (Robinson et al. 1989). Assuming conservatively that the economic value of animal pollinators worldwide is at least five times that in the United States, the contribution of animal pollination to world agriculture is estimated to

be \$200 billion per year (Table 2 and Figure 1).

Pollinator biodiversity is also an advantage in natural ecosystems, whose diversity of vegetation and habitat often requires pollinator species with varied characteristics (LaSalle and Gould 1993). For example, different flower sizes and shapes necessitate types of pollinators suited to the needs of particular flowers (Neff and Simpson 1993).

Habitat fragmentation and loss are causing precipitous declines in wild pollinators, thereby threatening their beneficial activities in both natural and agricultural systems. Specifically, habitat degradation adversely affects pollinator food sources, nesting sites, and mating sites. Diseases and pesticides also decimate pollination systems. In the United States, populations of wild bees are decreasing in agricultural regions (Richards 1993). In California, for instance, significant habitat alterations combined with pesticide use have led to the reduction of most wild bees, forcing farmers to rely on rented honeybee colonies for pollination.<sup>5</sup>

### Wild animals and ecotourism

Sport fishing, hunting, and associated recreational pursuits generate millions of dollars each year worldwide. For instance, the US public spends approximately \$29 billion per year on fishing (Coull 1993) and \$12 billion per year on hunting (USBC 1995). Thus, \$41 billion per year is a conservative estimate of the economic value of wild animals to the US economy (Table 2). Estimated worldwide expenditures for hunting and for fishing total approximately \$85 billion per year (Table 2).

The growing ecotourism industry generates an enormous amount of money for economies around the world. Nonconsumptive recreation, such as birdwatching, in the United States contributes approximately \$18 billion per year (Table 2; USDI 1991). Ecotourism is fast becoming an especially lucrative industry for some developing nations. For example,

ecotourism is the second largest industry in Costa Rica, where it generates \$500 million per year (Podgett and Begley 1996). Munasinghe and McNeely (1994) estimate that ecotourism contributes between \$0.5 and \$1 trillion per year to the world economy (Table 2 and Figure 1).

### Harvest of food and pharmaceuticals from the wild

In the United States, commercial and sport fisheries represent the largest proportion of the harvested wild biota, with 5.5 million tons harvested each year at a value of \$2.5 billion (Table 2; USBC 1995). Worldwide, the estimated 95 million tons of seafood harvested each year is valued at approximately \$82 billion (Thorpe et al. 1995). This figure does not include the contributions of commercially produced aquaculture and algal products (Table 2; Radmer 1996). Overall, fish provide less than 1% of the world's food (and less than 5% of protein; FAO 1991).

The 6 million tons of food products harvested annually from terrestrial wild biota in the United States include large and small animals such as deer and squirrels and products such as maple syrup, nuts, blueberries, and algae. Harvested wild blueberries are valued at \$25 million per year (Harker 1995), and the 6 million liters of US maple syrup produced each year (USDA 1995) are valued at \$57 million. In total, wild foods including seafood contribute an estimated \$3 billion per year to the US economy (Table 2; USBC 1995).

A world value for foods harvested from the wild cannot be extrapolated from US values because people in developing countries depend more extensively on wild biota for their food than Americans. A reasonable estimate is that \$90 billion per year in food and in related products are harvested from forests and used by approximately 300 million people in developing countries (Pimentel 1997a). This harvested food is sufficient to provide from 5% to 10% of the food that is consumed by people living in these forested areas. An equal amount of food, worth approximately \$90 billion per year (Pimentel et al. 1997a), is harvested from nonforested terrestrial areas in

<sup>5</sup>E. C. Mussen, 1996, personal communication. Department of Entomology, University of California, Davis, CA.

<sup>4</sup>See footnote 1.

the world, bringing the total to approximately \$180 billion per year in food and related products that are harvested from natural terrestrial ecosystems (Table 2 and Figure 1).

In the United States, pulp and timber products generate approximately \$8 billion per year (USBC 1995), whereas the worldwide return is estimated to be \$84 billion per year (Table 2; Groombridge 1992). In addition to food and wood products, plants with medicinal properties are harvested from the wild. Indeed, nearly half of the medicinal prescriptions that are now in use originated from a wild plant (Plotkin 1991), and between 35,000 and 70,000 species of plants are used directly as medicines (Farnsworth and Soejarto 1991). For instance, derivatives from 2500 plant species have been approved as medicines in India alone (Principe 1991).

Plant-based drugs and medicines in the United States have a market value of \$36 billion per year (USBC 1995), and those on the Asian market have a value of \$70.5 billion per year (Gerry 1995). Thus, we estimate that the economic return in the world market of plant-based drugs is worth more than \$200 billion per year. Of this estimate, over-the-counter plant-based drugs have an estimated market value of \$20 billion per year in the United States and \$84 billion per year worldwide (Table 2; Pearce and Moran 1994).

### Forests sequestering carbon dioxide

Trees, like all growing vegetation, sequester carbon dioxide and thereby help to reduce global warming. Rising temperatures and changing global rainfall patterns are likely to alter crop production. Global warming is also projected to melt some of the ice caps, which could cause the world sea level to rise, resulting in serious coastal flooding and damage to vast coastal regions.

Pearce (1991) estimates that a diverse tropical forest sequesters  $10 \text{ t} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$  of carbon. Based on his "damage avoided" approach, the net reduction of carbon by forests is worth \$20 per ton of carbon dioxide removed in terms of reducing the coastal damage that would result

from the sea level rise associated with global warming (Fankhauser 1993). Thus, for the 1.8 billion hectares of tropical forests (WRI 1994), approximately 2.5 t/ha of net carbon is sequestered each year, with an associated damage-avoided value of approximately \$90 billion per year. Pearce (1991) estimates that the  $1.5 \text{ t} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$  of carbon sequestered in the 1.5 billion hectares of world temperate forest has a total value of \$45 billion per year. The world total in damage avoided is thus \$135 billion per year (Table 2 and Figure 1). For the 210 million hectares of US forests, we calculate a total value of \$6 billion per year in damage avoided (Table 2). These estimates should be considered conservative because they are based on projected coastal damage from sea level rise and do not include the many other detrimental environmental effects of global warming on food crop production and on human health (WRI 1994).

### Costs of conserving biodiversity

Some aspects of conserving biodiversity are expensive, although they may return important dividends. For example, as of 1993, \$20 million had been spent on research and conservation to save the California condor (Cohn 1993), and the cost of possible measures to protect salmon in the Snake and Columbia rivers has been estimated at between \$2 and \$211 million (GAO 1993). Moreover, the costs of rearing even a nonendangered bird species such as those that are typically killed in oil spills can be highly expensive. For instance, the cost of replacing a bird that was killed by the Exxon Valdez oil spill was an average of \$800 per bird. Obviously, this type of conservation of biodiversity is extremely costly.

Other types of resource conservation not only protect biodiversity but also provide significant economic dividends at the same time. For example, biomass conservation aids in increasing species because all organisms, except for plants, which produce their own protoplasm, depend on the biomass from plants for energy and other nutrients. Thus, more biomass generally means that there are more species (Pimentel et al. 1992).

Increased biomass has numerous benefits in crop, pasture, and forest production. It reduces soil erosion, diseases, and rapid water runoff; improves recycling of soil nutrients and pest biocontrol; increases water percolation into the soil; and provides other economic benefits.

Conserving water resources and biodiversity saves money. Agriculture consumes approximately 80% of the total water per year in the United States annually. Conserving water in agriculture would be profitable for taxpayers and would increase water availability for biodiversity. Currently, approximately \$4.4 billion in public funds is used to subsidize water for western agriculture, and much of the water comes from the Colorado River (Pimentel et al. 1997b). Eliminating this enormous subsidy would conserve water, improve biodiversity in the overdrafted Colorado River, and save taxpayers billions of dollars.

### Conclusions

The estimated economic and environmental benefits from all biota (biodiversity), including their genes, are substantial. For the United States, their services contribute an estimated \$319 billion per year. Relative to the \$6 trillion per year of US gross domestic product (GDP), the services amount to 5% of GDP (USBC 1995). For the world, the benefits are estimated to be \$2928 billion per year, or approximately 11% of the total world economy of \$26 trillion per year.<sup>6</sup> These estimated benefits are clearly conservative. For example, another similar study estimates world economic benefits of biodiversity to be \$33,000 billion per year (Costanza et al. 1997).

Our study endeavored to increase the understanding of the many essential services that diverse species provide to humans. These services include organic waste disposal, soil formation, biological nitrogen fixation, crop and livestock genetics, biological control of pests, plant pollination, drugs and medicines, and the vast genetic resources that will be required for future sustainability of the environment and human society.

<sup>6</sup>N. Myers, 1996, personal communication. Oxford University, Oxford, UK.

The current rate of species extinction is now approximately from 1000 to 10,000 times higher than natural extinction rates and is reducing biodiversity. Growing human populations and their associated increase in activities are destroying natural and other habitats that are required for the survival of many plant and animal species. Some threats to agriculture, forestry, and natural ecosystems are related to the losses of pollinators, natural enemies of pests, and fishes. Pollution of ecosystems and the depletion of basic resources have reached dangerous levels. If future generations are to live in a safe, productive, and healthy environment, sound policies and effective conservation programs must be implemented to protect biodiversity (Pimentel et al. 1992) before it is too late for meaningful action.

## Acknowledgments

We thank the following people for reading an earlier draft of this article, for their many helpful suggestions, and, in some cases, for providing additional information: C. C. Delwiche, Professor Emeritus, University of Oregon, Corvallis, OR; Johanna Dobereiner, Centro Nacional de Pesquisa em Agrobiologia, Rio de Janeiro, Brazil; Jürg Huber, Federal Biological Research Centre, Darmstadt, Germany; Stephen R. Kellert, Yale University, New Haven, CT; Lori Lach, Tellus Institute, Boston, MA; John LaSalle, International Institute of Entomology, London; A. R. Main, University of Western Australia, Nedlands, Perth, Western Australia; Eric C. Mussen, University of California, Davis, CA; Norman Myers, Oxford University, Oxford; Ida N. Oka, Bogor Research Institute for Food Crops, Bogor, Indonesia; Maurizio G. Paoletti, Università Degli Studi di Padova, Padova, Italy; David Pearce, Center for Social and Economic Research on the Global Environment, University College, London; Charles Perrings, University of York, Heslington, York, UK; Jon K. Piper, The Land Institute, Salina, Kansas; Jorge Rabinovich, Universidad de Belgrano, Buenos Aires, Argentina; Peter H. Raven, Missouri Botanical Garden, St. Louis, MO; Walt Reid, World Resources

Institute, Washington, DC; Gene Robinson, University of Illinois, Urbana, IL; Bernhard Schmid and Irmi Seidl, University of Zurich, Zurich, Switzerland; Hope Shand, Rural Advancement Foundation International, Pittsboro, NC; V. Kerry Smith, Duke University, Durham, NC; David Takacs, California State University, Seaside, CA; Laura Westra, University of Windsor, Windsor, Ontario, Canada; Ingrid H. Williams, IACR-Rothamsted, Harpenden, Hertfordshire, UK; and Richard Cahoon, Celia Harvey, William Lesser, and Marcia H. Pimentel at Cornell University, Ithaca, NY.

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