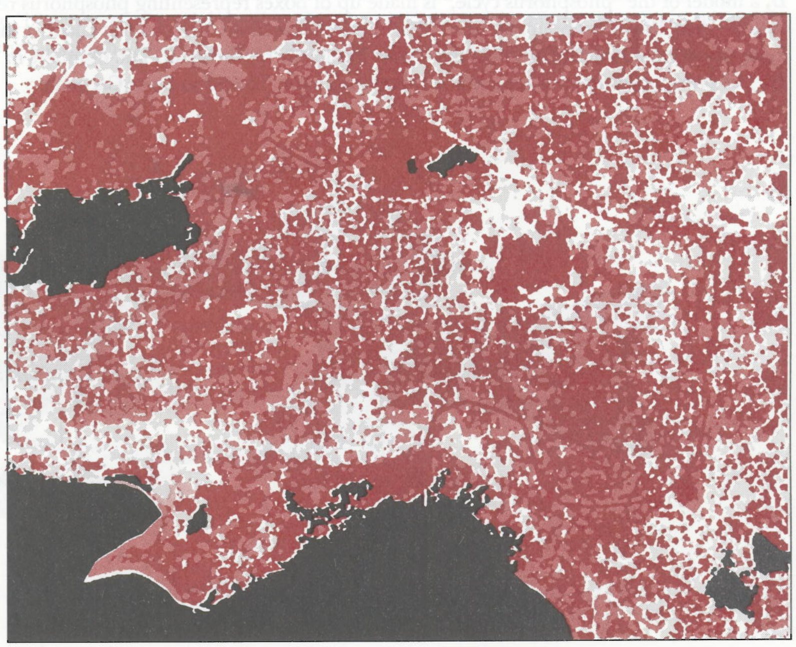
Environment and Society

4a

Dr. Bradley H. Brewster

A



B

Figure 1.1, A & B. Landscape Ecology uses maps and pictures of surfaces more than any other branch of ecology. Landscape images typically include several different subdivisions of the environment. **A.** A map of a 20-km diameter circle in northern Wisconsin (Trout Lake area), showing the distribution and connectedness of lakes and streams (color) and wetlands (gray) within a terrestrial environment (white). The map is recreated from a digitized USGS topological map. Thanks to Sarah Gergel. **B.** Recreated from a satellite image (taken from a Landsat Thematic Mapper satellite) of south-central Wisconsin (Madison area) taken in June, 1992. Black areas represent lakes and wetlands, with Lake Mendota at lower left. Vegetation is represented by color. Patterns of light gray and white delicately show the city radiating from the hub of the State Capitol at upper left-center. Thanks to David Bolgrien.

C

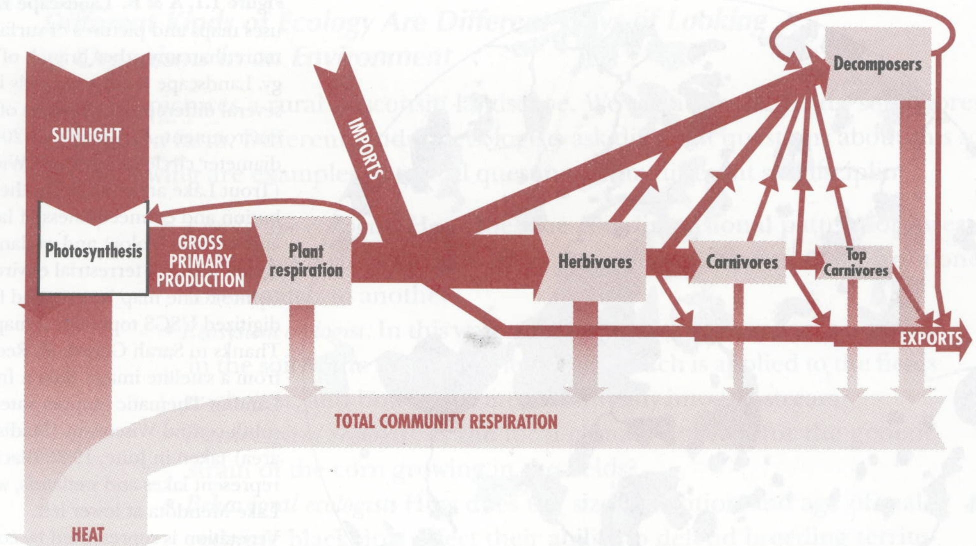
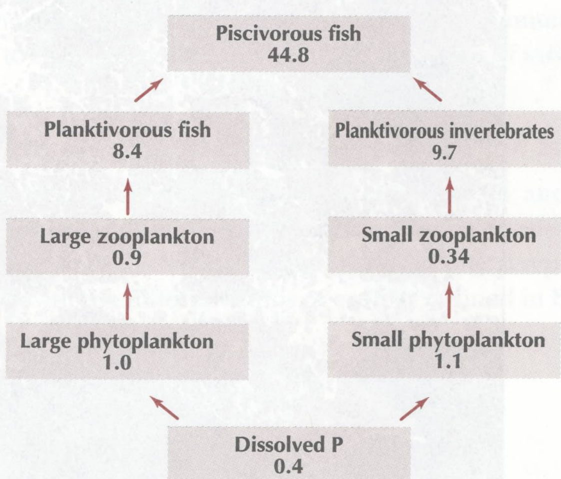
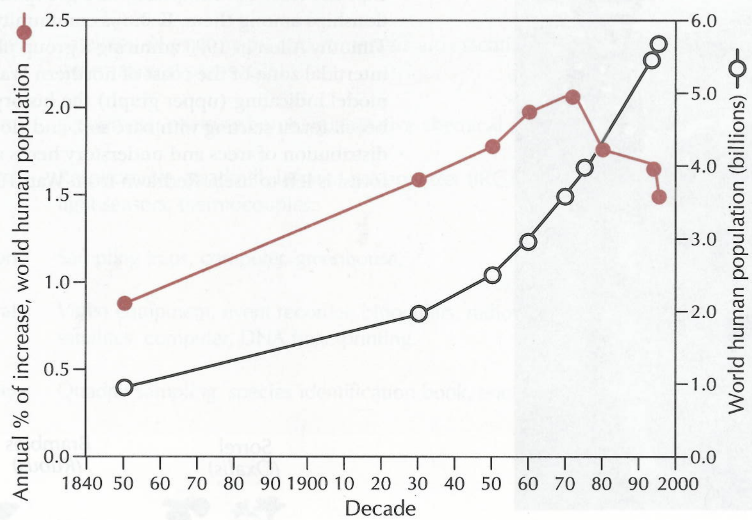


Figure 1.1. C & D. Ecosystem Ecology images often look like wiring or plumbing diagrams. The graphical model made up of boxes and arrows, now widely used in business plans, programming flow sheets, and many kinds of science, was first used by Charles Elton (1927), an early animal ecologist. **C** is a classic model, developed by H. T. Odum in 1957 to represent the flow of energy from the sun to photosynthetic organisms, to herbivores and predators. This model was intended to be applicable to streams, lakes, and coral reefs. It was developed in a paper that focused on the energetics of a stream flowing out of Silver Springs, Florida. In this figure boxes indicate "trophic levels" (see Chapter 4 for further explanation). **D,** a model of the "phosphorus cycle," is made up of boxes representing phosphorus reservoirs, with arrows indicating flow of phosphorus between reservoirs. The model is based on observations taken at the University of Notre Dame Environmental Research Center in the Upper Peninsula of Michigan. The numbers in the boxes represent the amount (kg) of phosphorus in each reservoir for the entire lake. Thanks to Steve Carpenter.

D





I

J

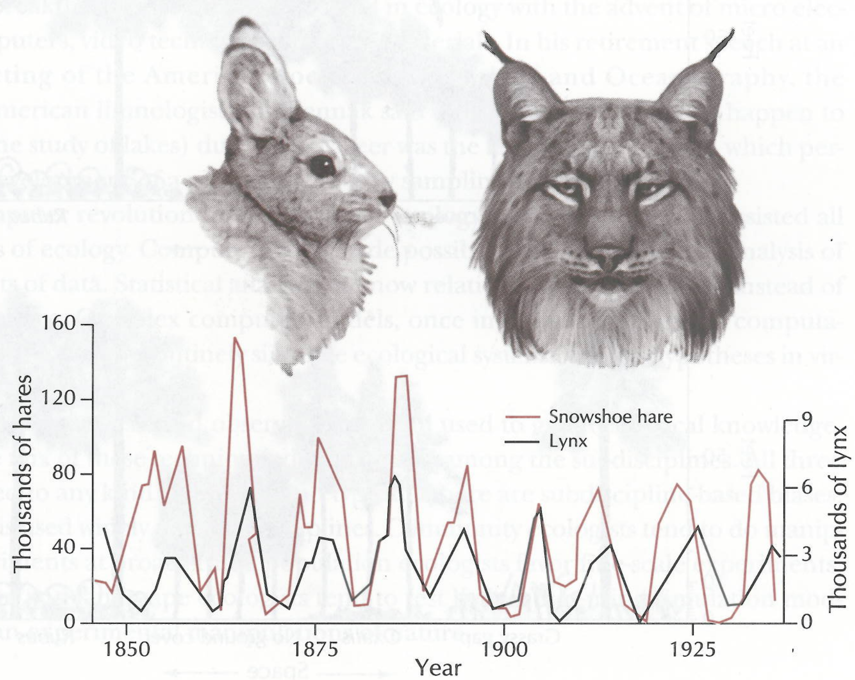
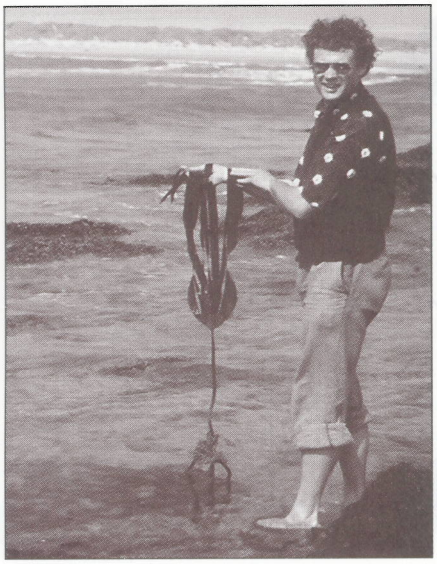


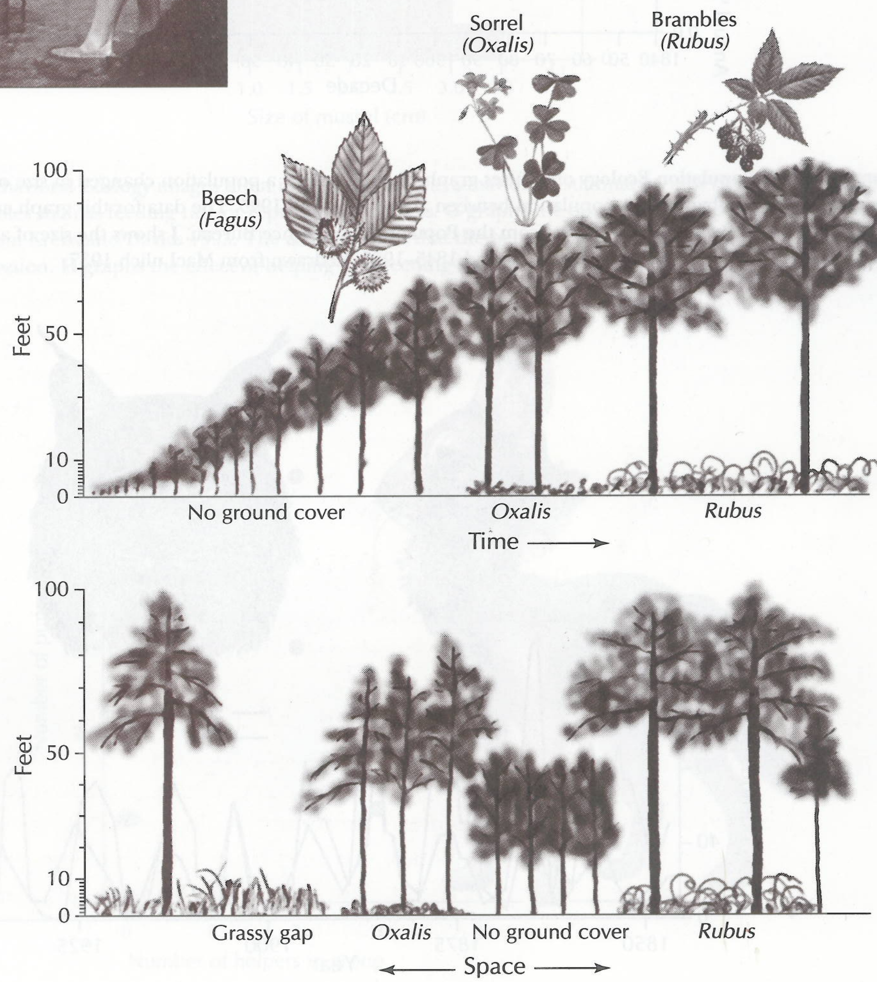
Figure 1.1. I & J. Population Ecology often uses graphs that show how a population changed in size over a period of time. **I** is a graph of the global human population between about 1850 and 1995. The data for this graph are given in Erlich et al. 1973, and *World Population Data Sheets* from the Population Reference Bureau. **J** shows the size of a population of Canadian lynx and snowshoe hares for the period 1845–1935. Redrawn from MacLulich 1937.



K

Figure 1.1. K & L. Community Ecology images usually express either the complexity of a group of species or relationships among them. **K** shows community ecologist Timothy Allen in 1980 admiring a group of species in the intertidal zone of the coast of northern Wales. **L** is a pictorial model indicating (upper graph) the history of growth of a beech forest starting with bare soil, and (lower graph) the distribution of trees and understory herbs after the mature forest is left to itself. Redrawn from Watt 1947.

L



Value of Diversity

Cary Fowler and Pat Mooney

(Chapter 3 in *Shattering: Food, Politics, and the Loss of Genetic Diversity*, University of Arizona Press 1990)

[Edited and abridged for readability and for the purposes of this class. ~ Dr. Bradley H. Brewster]

"The fate of all forms of life … depends on the continuity of variation. At the entrance to CERES, the Controlled Environment Research Laboratory in Canberra (Australia), there is the following inscription: 'Cherish the earth, for man will live by it forever.' We might have said with equal justification: 'Cherish variation, for without it life will perish.'"
~Sir Otto Frankel

Little is "natural in contemporary agriculture. It is not nature's way to allow large expanses of land to be planted to a single crop, much less to a single variety of that crop. As agriculture took hold and developed in ancient times, however, a certain fragile balance came to exist between plants and pests and diseases.

Primitive varieties—landraces—exhibited a great deal of genetic variation. A cursory look at a Neolithic wheat field would reveal differences from plant to plant. To be sure, pests and diseases struck, but their attacks were muted by the diversity and strength of the defenses accumulated by the plants during thousands of years of adaptation under agriculture. On the margin of many a field grew wild relatives of crops, which frequently crossed with those crops, infusing them with greater stamina and resistance. Moreover, fields were not contiguous; there remained ecological barriers to the spread and buildup of diseases. As a rule, diseases only rarely exploded into widespread epidemics. Crops were damaged, but not devastated.

But then the world changed—or at least perceptions of it did. The event was the visitation to Ireland of *Phytophtora infestans* in the 1830s.

A native of the Andes, the potato was unknown in Europe prior to the "discovery" of the New World. Potatoes were introduced into Spain in 1570 and into England and Ireland about 1590 or a few years earlier. For 250 years all potatoes grown in Europe were descendants of these two introductions.

In France, King Louis XVI became an advocate of the potato. In a neglected field near Paris he grew a wonderful crop of potatoes protected during the day by royal guards. Realizing that the peasants would be impressed by any crop so guarded, he cleverly withdrew the guards at night, allowing the peasants to raid the fields, which they did. Soon the king's goal was accomplished—all over France potatoes were growing.

In Ireland the potato became the staple crop of the poor. By the 1840s the average adult was eating nine to fourteen pounds a day. The summer of 1845 was a particularly good one for Irish farmers and reports from a number of countries indicate potato crops of "the most luxuriant character … promising abundant yield."

Then it happened. On September 11, the *Freeman's Journal* announced:

> We regret to have to state that we have had communications from more than one well-informed correspondent announcing the fact of what is called "cholera" in potatoes in Ireland, especially in the north. In one instance the party had been digging potatoes—the finest he had ever seen—from a particular field, and a particular ridge of that field up to Monday last; and on digging in the same ridge on Tuesday he found the tubers all blasted, and unfit for the use of man or beast.

The potatoes in the ground as well as those already harvested began to turn black and rot. An awful stench filled the countryside. The weather was blamed. Next year would be better.

But it was not. The failure of the potato crop was a disaster for the Irish poor, who were numerous. Though three-quarters of the land was devoted to cereal crops (which were producing fine harvests), nearly all of this was exported to England or used to pay rents to landlords, many of whom were foreign. At the time, four thousand people owned eighty percent of the land, while the annual earnings of a rural laborer rarely equaled the rent on a single acre of land. John Mitchel, an Irish journalist of the time, charged that "in 1847, during the Great Hunger, Ireland produced agricultural products to the value of

£44,958,120, enough to feed Ireland twice over, and continued to do so, but the people starved because with this produce the rent had to be paid." On occasion mobs attempted to prevent the grain from moving to the seaport for export, but such efforts were thwarted by the military.

The peasants could afford neither to keep nor to buy the grain they raised. Instead they lived on potatoes. A third of the Irish population was totally dependent on the potato for nourishment.

The British who ruled Ireland were concerned, but, as one observer noted at the time, "one must remember that the Irish had a terrible tendency to exaggerate." The British did repeal import duties on grain in order to lower the price of bread. But in the best of times, the poor could not afford bread—that was why they existed on potatoes.

Next the British imported corn and stored it in warehouses. But the Irish were unaccustomed to eating corn and the mills ill-equipped to process it. Meanwhile, Irish-raised wheat was being exported to Britain in huge quantities. Irish relief societies actually began to import grain from England at inflated prices—grain that had been grown in Ireland and exported because the people, now starving, were too poor to pay for it!

The British opposed giving food to the starving lest it encourage the idle poor. Charles Trevelyan, the British bureaucrat in charge of the government's famine policy in Ireland, finally shut down public works programs and ceased all other government relief in 1847, declaring in effect that the famine was over and voicing his concern that "the only way to prevent people from becoming habitually dependent on government is to bring operations to a close. Uncertainty about the new crop only makes it more necessary. … These things must be stopped now, or you run the risk of paralyzing all private enterprise." And with that statement, Trevelyan left Ireland to what he called "the operation of natural causes," and went on vacation to France. Knighted for his work in Ireland upon returning from France, Sir Charles Trevelyan set about writing a history of the Irish famine, which, predictably, he claimed had ended in August, 1847.

But the famine was not over. The winter of 1847-1848 saw corpses lying in the streets unburied for days. By the spring of 1849, the toll had become staggering. One county with a population of five thousand had over seven hundred people die in a two-week period. Some then—as now—said that the dreadful poverty of the people was caused by overpopulation. But as the population was decimated, the poverty remained. There was no appreciable rise in incomes. Considering emigration, Ireland's population for the century leading up to the famine was, according to Erna Bennett, "probably slightly higher than the British, but insignificantly so." Moreover, the amount of cultivated land per capita in Ireland immediately prior to the famine was similar to that of other European countries. Ireland was more densely populated than Denmark and Prussia, but less so than England, Wales, Scotland, or Belgium.

The famine continued for five years altogether. For five years Ireland's potatoes rotted. One to two million people died and as many migrated to North America, including the ancestors of two American presidents—Kennedy and Reagan.

It was not the weather that struck down Ireland's potatoes in the 1840s; it was *Phytophtora infestans*, a potato blight. The potatoes grown in Europe—genetically limited, as we have seen—were not resistant to this disease, and their lack of resistance allowed the blight to reach epidemic proportions. Luckily not all potatoes were vulnerable. Among the thousands of distinct types in the Andes and in Mexico, resistance was located. Without it, potatoes probably would not be a major crop in the developed world today.

But the blight has consistently been blamed for the famine. As devastating as the disease was to potatoes, it was the social system, by allowing few to own and control so much, that caused the famine. How else can we explain the fact that eighty percent of the countryside was still being grazed, not cultivated, and that grain continued to be exported at a time when hundreds of thousands were perishing? Even as people were starving, Ireland produced enough food for everyone. The Irish themselves said: "God sent the blight; the English brought the famine."

Potatoes were the first crop in modern history to be devastated by lack of resistance—and the first crop to be rescued by the wealth of defenses built up over thousands of years in its center of diversity. Thus the Irish potato famine stands both as the most dramatic warning of the dangers of genetic uniformity and the clearest example of the value of preserving genetic diversity.

Differences in the performance of different crop varieties had long been noted. Various Greek and Roman writers recorded their observation on this matter. But little use of this knowledge was made until the advent of modern plant breeding in the 1800s and the rediscovery of Gregor Mendel's laws of heredity at the turn of the century.

With this knowledge, plant breeders were able to use the diverse characteristics of landraces developed over thousands of years to fashion new crop varieties designed for particular situations. By carefully selecting for the desired characteristics, breeders could "weed out" unwanted traits and arrive at a "pure line," a variety that was uniform and reproduced this uniformity.

The diversity and variability of the old landraces used in early breeding programs were thus whittled down to a pure line. And often one pure line was bred with another to create a hybrid. In the field these genetically restricted varieties replaced the wide open diversity, the "harmonious disorder" of the landraces.

> A pure line mentality, convinced that variation was bad, uniformity was good, and off-types in the field somehow immoral, developed. Symptoms of the mental climate could be found in crop judging contests, ribbons awarded at county and state fairs, crop improvement associations, seed certification agencies, and in some provisions of state and federal seed acts. It did not seem to occur to anyone that a deliberate mixture of cultivars could be a useful alternative to pure line culture. Although grain is considered bad husbandry and a slightly less than mortal sin to be kept hidden on the back forty off the road.

Though the new varieties were clearly superior in some respects—yield being the most obvious—they sometimes lacked the breadth of resistance, or a trait like cold tolerance, contained in the landraces. Simply put, the landraces would not have survived as long as they had under harsh conditions without fertilizers or pesticides if they had not been adapting effectively. Contributing to their success was the spatial heterogeneity provided by early farming systems. Mixed cropping made it difficult for pests and diseases to build up excessively. With the new varieties the flexibility of general adaptation and resistance was traded for something more focused and inflexible. Replacement of landraces with new, pure line varieties planted over thousands of acres opened the way for pests and diseases to attack the uniform, inbred plants. In a field of landraces a pest might gobble up one plant but find the next one different enough to be distasteful. In a field of modern varieties, if the first tasted good, they were all going to taste good.

In the 1870s coffee rust essentially wiped out the coffee industry in Ceylon (now Sri Lanka), India, East Asia, and parts of Africa. As a result, England became a nation of tea drinkers. Epidemics hit cotton in the 1890s. And in 1904, an epidemic of stem rust struck the U.S. wheat crop. By 1905, what is probably the oldest program designed to develop disease resistance in this crop was begun by the U.S. Department of Agriculture.

The race continued. Other epidemics followed. In 1917, "wheatless" days were declared in the U.S. in response to an epidemic. Twenty-six years later and half a world away, brown spot disease devastated the Indian rice crop, touching off the infamous Bengal famine. In the 1940s, cultivars accounting for eighty percent of the U.S. oat crop were eliminated, and oats experienced more problems in the 1950s. Then the early 1970s, corn blight struck in the U.S., sparking concern over genetic uniformity in the nation's crops. And a major failure of the Soviet wheat crop, caused in part by the large-scale planting of an inappropriate variety, precipitated the "Russian grain deal" and dramatic (and ultimately costly) shifts in American farm policy.

Each time resistance was needed. And each time it was found in the centers of diversity, in landraces that had somehow escaped homogenization, or in those crops' wild relatives.

As use of the pure line and hybrid varieties increased, so did pest and disease problems. The greater pest and disease problems grew, the more farmers turned to chemicals to solve them. In 1945, less than 200 million pounds of pesticides were employed in the U.S. Thirty years later the total had risen to 1,600 million pounds.

But the chemicals did not solve the problems. It could even be argued that as pesticides use increased, so did pest problems. With all the increased "firepower" in the hands of farmers, it might be expected that the pest rebellion would have been put down. But in the last forty years the percentage of the annual crop lost to insects has doubled in the U.S. Losses due to diseases have also increased. There are reasons for this.

Much of agriculture's pest control work is done by "beneficial" insects that feed on or otherwise control "harmful" insects; or by spatial heterogeneity. In a "natural" setting there are more harmful than beneficial predatory insects. If there were not, the beneficial insects would begin dying off from lack of food. A one-to-one ratio between harmful and beneficial insects would mean that the useful insect's first meal would probably be its last.

Most pesticides kill both useful insects and agricultural pests without distinction. One corporation, Rockwell International, advertised in a magazine that its pesticide would "kill every bug you've got" and all the insects pictured were creatures that never harm crops. A pest problem may be alleviated temporarily by a pesticide as it kills insects at hand. But, as Dr. Carl Huffaker of the University of California says, "When we kill a pest's natural enemies, we inherit their work." When the pesticide dissipates or is washed away by rain, the harmful insects multiply rapidly. The population of beneficial insects—small to begin with and now completely decimated—cannot recover as quickly. The result: harmful insects return with a vengeance, this time with even less to stop them.

It is becoming common knowledge that insects are developing resistance to the pesticides that once killed them. Resistance to DDT began appearing among crop-eating insects just six years after introduction of that infamous pesticide. Most people realize that today's super pest could enjoy several doses of yesterday's pesticides for dessert, ask for more, and live to tell about it. Over four hundred species of pests have now developed resistance to the chemicals that once destroyed them. More than a million chemicals have already been screened for their effectiveness as pesticides and yet "the progress of resistance may outpace the discovery of effective new materials."

Insects can also learn to evade the plant's natural resistance. In an experiment conducted by the International Rice Research Institute (IRRI), plant pathologies raised the troublesome brown planthopper on a rather poor quality, but brown planthopper-resistant rice variety by the name of Mudgo. The insect, which is now the most serious pest in Asia according to T. T. Chang of IRRI, was unknown to rice workers in the early 1960s. In this experiment many brown planthoppers starved to death rather than eat Mudgo. On average the first generation of planthoppers lived only 4.2 days, but that was long enough for them to produce a new generation. The new generation did not find Mudgo quite as distasteful. By the tenth generation, the planthoppers were indicating that Mudgo was all right. They lived an average of sixteen days eating another else, which is about as long as they lasted feasting on one of their favorite, susceptible rice varieties.

With insects developing both immunity to pesticides and a taste for resistant varieties so quickly, it is little wonder that the average life span of a new cultivar has, in the memorable words of Lawrence Hills, "been reduced to that of a pop record." Kenyan wheats, to cite but one example, last an average of 4.3 years before they have to be pulled off the market and replaced by a new variety.

Like insects, diseases also adapt both to chemicals and to the genetic defenses of plants. Diseases mutate, developing new races to overcome the resistance of plants and the farmers' chemicals. "Race I" of the standard wheat stem rust was identified in 1917. Fifty years later, three hundred were known. Like insects, plant diseases have coevolved with their host organism. They are not in the business of becoming extinct. By adapting to their changing environment they are able to survive. And survive they do.

As the pest chalk up victories on the battlefield, chemical company bravado rises in pitch. Government regulations slowing down their ability to add to the chemical load already in use, claim the pesticide manufacturers, have prevented them from winning the war. In one startling editorial in a Down Chemical Company newsletter, Dr. C. A. Goring, director of agricultural products research for Dow, said: "Given the opportunity, the web of man-made chemical technology could continue to grow in beauty and diversity creating many new and beautiful species, eliminating some old species and relegating others to more specific ecological niches." Did you catch that? "Given the opportunity," Dow's chemicals will create a few new species, eliminate some species (might we ask which?), and assign others to "more specific ecological niches." Anyone opposing this plan, according to Goring, is an "anti-technologist." After all, he continues, "the chemicals we make are no different from the ones God makes."

As agriculture developed in ancient times, the balance between plants and pest and diseases rarely got too far out of line. A disease too successful would ultimately eliminate itself! Plants survived. Pests and diseases survived. With the creation of pure line varieties, however, much resistance was lost as the diversity of the landraces was reduced to create uniform varieties. Plant species that had had to rely on their own natural defenses and on mixed cropping systems for thousands of years were suddenly forced to depend on man to help them resist new or stronger pests. Thus breeding programs were established to re-insert resistance into crop varieties that were now under constant attack.

When plant breeders settle down to the long and expensive job of developing a disease resistant variety, their first line of attack is to look for that resistance in other modern varieties; then they try landraces. Modern varieties and their breeding stocks give the breeder the least trouble, because they are unusually similar in other respects to the variety desired. It takes less effort to eliminate the undesirable characteristics while obtaining the needed resistance. Landraces, because they have survived so long among pests and diseases in the centers of diversity, offer a wealth of potential resistance. But they are not as similar to the end product desired and some pains must be taken to eliminate unwanted characteristics as the resistance is obtained.

Canada's famous wheats were produced by breeding varieties and landraces from Australia, England, Kenya, Egypt, India, Poland, Portugal, and the Middle East. And in the U.S., a Chinese spinach variety "rescued Virginia's spinach industry from ruin." A thorough listing of such examples would take many books. Suffice it to say that the "primitive" varieties developed by our ancestors continue to play an integral role in the maintenance of modern crop varieties.

When all else fails and resistance or some other desired characteristic cannot be found in cultivated types, the plant breeders will turn to closely related wild or weedy plants for the needed genes. Breeders call these plants "wild relatives." Working with wild relatives is often difficult. For every desirable characteristic obtained, a number of completely unacceptable ones must be bred out. Ridding the new variety of wild and weedy characteristics can mean years of extra work for the breeder, hence the use of wild relatives in breeding programs is usually a sign of either desperation or courage on the breeder's part. Many plant breeders do not even know, could not even recognize, the wild relatives of the crops they specialize in breeding.

The diversity of wild relatives has enabled them to survive longer than the oldest cultivated variety—and to survive without human assistance. If their genetic resistance had failed them, they would have become extinct long ago. Thus, as sources of resistance, wild relatives are a treasure.

Wild relatives have now been used in the breeding programs of virtually every cultivated crop. Sugarcane is "an example of a commercial crop that has been completely salvaged" by the use of wild relatives. The same could probably be said of strawberries and sunflowers using genes found in North America.

Wild species from Central and South America offer the only known source of resistance to the most serious disease that strikes black pepper. And in peanuts, wild species are now "the main source of resistance to pests and diseases." Likewise, potato breeders are becoming more and more dependent on wild relatives. In the Federal Republic of Germany, nine out of ten potato seedlings have wild species or primitive landraces in their backgrounds.

Tomatoes "could not be grown commercially at all in the U.S.," according to Jack Harlan, without the resistance they have developed from wild species. For at least nineteen disorders of tomatoes, wild tomato species are the principle source of resistance. Wild species of tomato offer some interesting possibilities for future breeding work. One of the world's leading experts on tomatoes, Dr. Charles Rick of the University of California, found a number of wild tomatoes growing along the beach on one of the Galapagos Islands. Barely five meters (16.5 feet) from the high tide line, these plants were exposed to Pacific salt spray and very salty soil. Back at the University of

California at Davis, Rick's colleagues found that these tomatoes could be grown hydroponically in a culture "gradually adjusted to full-strength sea water."

After a four-year program which tested seventeen thousand rice accessions and over one hundred wild taxa, resistance to grassy stunt virus was found in just one population of *Oxyza nirvana* from India. When a new strain of the virus appeared in 1982 more screening was forced. After arduous testing, resistance was again found in wild species. And wild species have helped give potatoes resistance to *Phytophtora infestans*, of Irish potato famine fame. In 1951, an epidemic of barley yellow dwarf virus broke out in California. The search for resistance took breeders to one gene in an Ethiopian barley.

Chocolate and chocolate-lovers were delivered from twin curses of witches' broom and swollen shoot, two diseases that strike cacao, from which chocolate is made. Again, wild and semi-wild species furnished resistance. Wild species even show promise of helping the nutritional qualities of wheat, rice, oats, soybeans, and a number of vegetable crops. And others, like some of the bramble fruits, are being dethroned through breeding programs using wild plants.

Robert and Christine Prescott-Allen estimate that between 1976 and 1980, genetic material from wild relatives contributed $340 million per year in yield and disease resistance to U.S. farmers. According to the Prescott-Allens, wild germplasm has contributed $66 billion to the American economy—an amount greater than the total international debt of Mexico and the Philippines combined.

Primitive and wild relatives of crops have become so essential that Jack Harlan—arguably the scientist with the broadest knowledge of their role in agriculture—was moved to say that the "wild relatives stand between man and starvation."

Years ago, Vavilov described plant breeding as "evolution at the will of man." Like any kind of evolution, plant breeding requires variation. Artists create paintings using palettes covered with colors. Plant breeders fashion new varieties using the genetic variation within a crop. Robbing the breeder of this variation is like taking colors from the artist. It diminishes what is possible. If too much variation is lost, little or not evolution is possible. Eventually, the crop succumbs and becomes extinct.

Without the landraces and wild relatives, our modern crop varieties would be incapable of changing, of evolving, of adapting to new conditions, or stronger pests. Like so many things in this world, the new depends on the old. Without the old varieties, the new varieties could not continue. They simply could not survive. And herein lies the irony. In the long run, the future of agriculture and the very survival of crops depends not so much on the fancy hybrids we see in the fields, but on the wild species growing along the fence rows, and the primitive types tended by the world's peasant farmers in the centers of diversity. Without these wild species and old landraces, there would be no agriculture.

The value of the world's ecosystem services and natural capital

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The services of ecological systems and the natural capital stocks that produce them are critical to the functioning of the Earth's life-support system. They contribute to human welfare, both directly and indirectly, and therefore represent part of the total economic value of the planet. We have estimated the current economic value of 17 ecosystem services for 16 biomes, based on published studies and a few original calculations. For the entire biosphere, the value (most of which is outside the market) is estimated to be in the range of US\$16–54 trillion (10^{12}) per year, with an average of US\$33 trillion per year. Because of the nature of the uncertainties, this must be considered a minimum estimate. Global gross national product total is around US\$18 trillion per year.

Because ecosystem services are not fully 'captured' in commercial markets or adequately quantified in terms comparable with economic services and manufactured capital, they are often given too little weight in policy decisions. This neglect may ultimately compromise the sustainability of humans in the biosphere. The economies of the Earth would grind to a halt without the services of ecological life-support systems, so in one sense their total value to the economy is infinite. However, it can be instructive to estimate the 'incremental' or 'marginal' value of ecosystem services (the estimated rate of change of value compared with changes in ecosystem services from their current levels). There have been many studies in the past few decades aimed at estimating the value of a wide variety of ecosystem services. We have gathered together this large (but scattered) amount of information and present it here in a form useful for ecologists, economists, policy makers and the general public. From this synthesis, we have estimated values for ecosystem services per unit area by biome, and then multiplied by the total area of each biome and summed over all services and biomes.

Although we acknowledge that there are many conceptual and empirical problems inherent in producing such an estimate, we think this exercise is essential in order to: (1) make the range of potential values of the services of ecosystems more apparent; (2) establish at least a first approximation of the relative magnitude of global ecosystem services; (3) set up a framework for their further analysis; (4) point out those areas most in need of additional research; and (5) stimulate additional research and debate. Most of the problems and uncertainties we encountered indicate that our estimate represents a minimum value, which would probably increase: (1) with additional effort in studying and valuing a broader range of ecosystem services; (2) with the incorporation of more realistic representations of ecosystem dynamics and interdependence; and (3) as ecosystem services become more stressed and 'scarce' in the future.

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Ecosystem functions and ecosystem services

Ecosystem functions refer variously to the habitat, biological or system properties or processes of ecosystems. Ecosystem goods (such as food) and services (such as waste assimilation) represent the benefits human populations derive, directly or indirectly, from ecosystem functions. For simplicity, we will refer to ecosystem goods and services together as ecosystem services. A large number of functions and services can be identified[1–4]. Reference 5 provides a recent, detailed compendium on describing, measuring and valuing ecosystem services. For the purposes of this analysis we grouped ecosystem services into 17 major categories. These groups are listed in Table 1. We included only renewable ecosystem services, excluding non-renewable fuels and minerals and the atmosphere. Note that ecosystem services and functions do not necessarily show a one-to-one correspondence. In some cases a single ecosystem service is the product of two or more ecosystem functions whereas in other cases a single ecosystem function contributes to two or more ecosystem services. It is also important to emphasize the interdependent nature of many ecosystem functions. For example, some of the net primary production in an ecosystem ends up as food, the consumption of which generates respiratory products necessary for primary production. Even though these functions and services are interdependent, in many cases they can be added because they represent 'joint products' of the ecosystem, which support human welfare. To the extent possible, we have attempted to distinguish joint and 'addable' products from products that would represent 'double counting' (because they represent different aspects of the same service) if they were added. It is also important to recognize that a minimum level of ecosystem 'infrastructure' is necessary in order to allow production of the range of services shown in Table 1. Several authors have stressed the importance of this 'infrastructure' of the ecosystem itself as a contributor to its total value[6,7]. This component of the value is not included in the current analysis.

Natural capital and ecosystem services

In general, capital is considered to be a stock of materials or information that exists at a point in time. Each form of capital stock generates, either autonomously or in conjunction with services from other capital stocks, a flow of services that may be used to transform materials, or the spatial configuration of materials, to enhance the welfare of humans. The human use of this flow of services may or may not leave the original capital stock intact. Capital stock takes different identifiable forms, most notably in physical forms including natural capital, such as trees, minerals, ecosystems, the atmosphere and so on; manufactured capital, such as machines and buildings; and the human capital of physical bodies. In addition, capital stocks can take intangible forms, especially as information such as that stored in computers and in individual human brains, as well as that stored in species and ecosystems.

Ecosystem services consist of flows of materials, energy, and information from natural capital stocks which combine with manufactured and human capital services to produce human welfare. Although it is possible to imagine generating human welfare without natural capital and ecosystem services in artificial 'space colonies', this possibility is too remote and unlikely to be of

Table 1 Ecosystem services and functions used in this study

Number	Ecosystem service*	Ecosystem functions	Examples
1	Gas regulation	Regulation of atmospheric chemical composition.	CO_2/O_2 balance, O_3 for UVB protection, and SO_x levels.
2	Climate regulation	Regulation of global temperature, precipitation, and other biologically mediated climatic processes at global or local levels.	Greenhouse gas regulation, DMS production affecting cloud formation.
3	Disturbance regulation	Capacitance, damping and integrity of ecosystem response to environmental fluctuations.	Storm protection, flood control, drought recovery and other aspects of habitat response to environmental variability mainly controlled by vegetation structure.
4	Water regulation	Regulation of hydrological flows.	Provisioning of water for agricultural (such as irrigation) or industrial (such as milling) processes or transportation.
5	Water supply	Storage and retention of water.	Provisioning of water by watersheds, reservoirs and aquifers.
6	Erosion control and sediment retention	Retention of soil within an ecosystem.	Prevention of loss of soil by wind, runoff, or other removal processes, storage of stilt in lakes and wetlands.
7	Soil formation	Soil formation processes.	Weathering of rock and the accumulation of organic material.
8	Nutrient cycling	Storage, internal cycling, processing and acquisition of nutrients.	Nitrogen fixation, N, P and other elemental or nutrient cycles.
9	Waste treatment	Recovery of mobile nutrients and removal or breakdown of excess or xenic nutrients and compounds.	Waste treatment, pollution control, detoxification.
10	Pollination	Movement of floral gametes.	Provisioning of pollinators for the reproduction of plant populations.
11	Biological control	Trophic-dynamic regulations of populations.	Keystone predator control of prey species, reduction of herbivory by top predators.
12	Refugia	Habitat for resident and transient populations.	Nurseries, habitat for migratory species, regional habitats for locally harvested species, or overwintering grounds.
13	Food production	That portion of gross primary production extractable as food.	Production of fish, game, crops, nuts, fruits by hunting, gathering, subsistence farming or fishing.
14	Raw materials	That portion of gross primary production extractable as raw materials.	The production of lumber, fuel or fodder.
15	Genetic resources	Sources of unique biological materials and products.	Medicine, products for materials science, genes for resistance to plant pathogens and crop pests, ornamental species (pets and horticultural varieties of plants).
16	Recreation	Providing opportunities for recreational activities.	Eco-tourism, sport fishing, and other outdoor recreational activities.
17	Cultural	Providing opportunities for non-commercial uses.	Aesthetic, artistic, educational, spiritual, and/or scientific values of ecosystems.

* We include ecosystem 'goods' along with ecosystem services.

much current interest. In fact, one additional way to think about the value of ecosystem services is to determine what it would cost to replicate them in a technologically produced, artificial biosphere. Experience with manned space missions and with Biosphere II in Arizona indicates that this is an exceedingly complex and expensive proposition. Biosphere I (the Earth) is a very efficient, least-cost provider of human life-support services.

Thus we can consider the general class of natural capital as essential to human welfare. Zero natural capital implies zero human welfare because it is not feasible to substitute, in total, purely 'non-natural' capital for natural capital. Manufactured and human capital require natural capital for their construction[7]. Therefore, it is not very meaningful to ask the total value of natural capital to human welfare, nor to ask the value of massive, particular forms of natural capital. It is trivial to ask what is the value of the atmosphere to humankind, or what is the value of rocks and soil infrastructure as support systems. Their value is infinite in total.

However, it is meaningful to ask how changes in the quantity or quality of various types of natural capital and ecosystem services may have an impact on human welfare. Such changes include both small changes at large scales and large changes at small scales. For example, changing the gaseous composition of the global atmosphere by a small amount may have large-scale climate change effects that will affect the viability and welfare of global human populations. Large changes at small scales include, for example, dramatically changing local forest composition. These changes may dramatically alter terrestrial and aquatic ecosystems, having an impact on the benefits and costs of local human activities. In general, changes in particular forms of natural capital and ecosystem services will alter the costs or benefits of maintaining human welfare.

Valuation of ecosystem services

The issue of valuation is inseparable from the choices and decisions we have to make about ecological systems[6,8]. Some argue that valuation of ecosystems is either impossible or unwise, that we cannot place a value on such 'intangibles' as human life, environmental aesthetics, or long-term ecological benefits. But, in fact, we do so every day. When we set construction standards for highways, bridges and the like, we value human life (acknowledged or not) because spending more money on construction would save lives. Another frequent argument is that we should protect ecosystems for purely moral or aesthetic reasons, and we do not need valuations of ecosystems for this purpose. But there are equally compelling moral arguments that may be in direct conflict with the moral argument to protect ecosystems; for example, the moral argument that no one should go hungry. Moral arguments translate the valuation and decision problem into a different set of dimensions and a different language of discourse[6]; one that, in our view, makes the problem of valuation and choice more difficult and less explicit. But moral and economic arguments are certainly not mutually exclusive. Both discussions can and should go on in parallel.

So, although ecosystem valuation is certainly difficult and fraught with uncertainties, one choice we do not have is whether or not to do it. Rather, the decisions we make as a society about ecosystems imply valuations (although not necessarily expressed in monetary terms). We can choose to make these valuations explicit or not; we can do them with an explicit acknowledgement of the huge uncertainties involved or not; but as long as we are forced to make choices, we are going through the process of valuation.

The exercise of valuing the services of natural capital 'at the margin' consists of determining the differences that relatively small changes in these services make to human welfare. Changes in quality or quantity of ecosystem services have value insofar as they either change the benefits associated with human activities or change the costs of those activities. These changes in benefits and costs either have an impact on human welfare through established markets or through non-market activities. For example, coral reefs provide habitats for fish. One aspect of their value is to increase and concentrate fish stocks. One effect of changes in coral reef quality or quantity would be discernible in commercial fisheries markets, or in recreational fisheries. But other aspects of the value of coral reefs, such as recreational diving and biodiversity conservation, do not show up completely in markets. Forests provide timber materials through well established markets, but the associated habitat values of forests are also felt through unmarketed recreational activities. The chains of effects from ecosystem services to human welfare can range from extremely simple to exceedingly complex. Forests provide timber, but also hold soils and moisture, and create microclimates, all of which contribute to human welfare in complex, and generally non-marketed ways.

Valuation methods

Various methods have been used to estimate both the market and non-market components of the value of ecosystem services[9–16]. In this analysis, we synthesized previous studies based on a wide variety of methods, noting the limitations and assumptions underlying each.

Many of the valuation techniques used in the studies covered in our synthesis are based, either directly or indirectly, on attempts to estimate the 'willingness-to-pay' of individuals for ecosystem services. For example, if ecological services provided a \$50 increment to the timber productivity of a forest, then the beneficiaries of this service should be willing to pay up to \$50 for it. In addition to timber production, if the forest offered non-marketed, aesthetic, existence, and conservation values of \$70, those receiving this non-market benefit should be willing to pay up to \$70 for it. The total

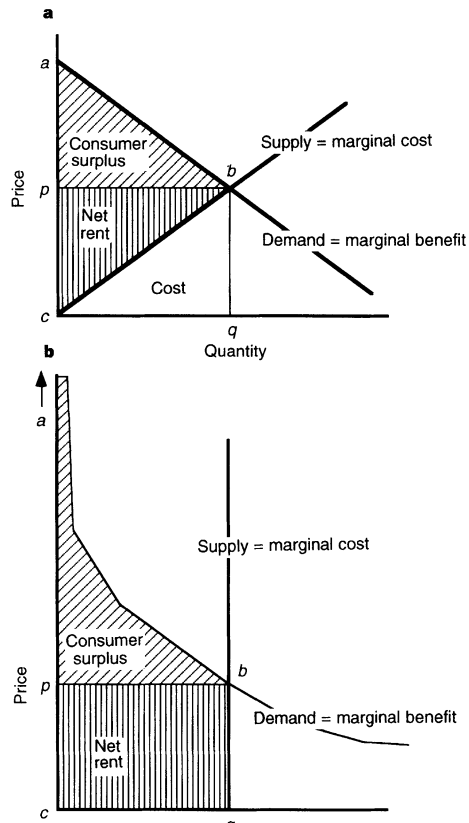

Figure 1 Supply and demand curves, showing the definitions of cost, net rent and consumer surplus for normal goods (**a**) and some essential ecosystem services (**b**). See text for further explanation.

Table 2 Summary of average global value of annual ecosystem services

Biome	Area (ha × 10^6)	Ecosystem serivces (1994 US\$ ha^{-1} yr^{-1}) 1 Gas regulation	2 Climate regulation	3 Disturbance regulation	4 Water regulation	5 Water supply	6 Erosion control	7 Soil formation	8 Nutrient cycling	9 Waste treatment	10 Pollination	11 Biological control	12 Habitat/ refugia	13 Food production	14 Raw materials	15 Genetic resources	16 Recreation	17 Cultural	Total value per ha (\$ ha^{-1} yr^{-1})	Total global flow value (\$ yr^{-1} × 10^9)
Marine	36,302																		577	20,949
Open ocean	33,200	38							118			5		15	0			76	252	8,381
Coastal	3,102			88					3,677			38	8	93	4		82	62	4,052	12,568
Estuaries	180			567					21,100			78	131	521	25		381	29	22,832	4,110
Seagrass/ algae beds	200								19,002						2				19,004	3,801
Coral reefs	62			2,750						58		5	7	220	27		3,008	1	6,075	375
Shelf	2,660								1,431			39		68	2			70	1,610	4,283
Terrestrial	15,323																		804	12,319
Forest	4,855		141	2	2	3	96	10	361	87		2		43	138	16	66	2	969	4,706
Tropical	1,900		223	5	6	8	245	10	922	87				32	315	41	112	2	2,007	3,813
Temperate/boreal	2,955		88		0			10		87		4		50	25		36	2	302	894
Grass/rangelands	3,898	7	0		3		29	1		87	25	23		67		0	2		232	906
Wetlands	330	133		4,539	15	3,800				4,177			304	256	106		574	881	14,785	4,879
Tidal marsh/ mangroves	165			1,839						6,696			169	466	162		658		9,990	1,648
Swamps/ floodplains	165	265		7,240	30	7,600				1,659			439	47	49		491	1,761	19,580	3,231
Lakes/rivers	200				5,445	2,117				665				41			230		8,498	1,700
Desert	1,925																			
Tundra	743																			
Ice/rock	1,640																			
Cropland	1,400										14	24		54					92	128
Urban	332																			
Total	51,625	1,341	684	1,779	1,115	1,692	576	53	17,075	2,277	117	417	124	1,386	721	79	815	3,015		33,268

Numbers in the body of the table are in \$ ha^{-1} yr^{-1}. Row and column totals are in \$ yr^{-1} × 10^9, column totals are the sum of the products of the per ha services in the table and the area of each biome, not the sum of the per ha services themselves. Shaded cells indicate services that do not occur or are known to be negligible. Open cells indicate lack of available information.

value of ecological services would be \$120, but the contribution to the money economy of ecological services would be \$50, the amount that actually passes through markets. In this study we have tried to estimate the total value of ecological services, regardless of whether they are currently marketed.

Figure 1 shows some of these concepts diagrammatically. Figure 1a shows conventional supply (marginal cost) and demand (marginal benefit) curves for a typical marketed good or service. The value that would show up in gross national product (GNP) is the market price *p* times the quantity *q*, or the area *pbqc*. There are three other relevant areas represented on the diagram, however. The cost of production is the area under the supply curve, *cbq*. The 'producer surplus' or 'net rent' for a resource is the area between the market price and the supply curve, *pbc*. The 'consumer surplus' or the amount of welfare the consumer receives over and above the price paid in the market is the area between the demand curve and the market price, *abp*. The total economic value of the resource is the sum of the producer and consumer surplus (excluding the cost of production), or the area *abc* on the diagram. Note that total economic value can be greater or less than the price times quantity estimates used in GNP.

Figure 1a refers to a human-made, substitutable good. Many ecosystem services are only substitutable up to a point, and their demand curves probably look more like Fig. 1b. Here the demand approaches infinity as the quantity available approaches zero (or some minimum necessary level of services), and the consumer surplus (as well as the total economic value) approaches infinity. Demand curves for ecosystem services are very difficult, if not impossible, to estimate in practice. In addition, to the extent that ecosystem services cannot be increased or decreased by actions of the economic system, their supply curves are more nearly vertical, as shown in Fig. 1b.

In this study we estimated the value per unit area of each ecosystem service for each ecosystem type. To estimate this 'unit value' we used (in order of preference) either: (1) the sum of consumer and producer surplus; or (2) the net rent (or producer surplus); or (3) price times quantity as a proxy for the economic value of the service, assuming that the demand curve for ecosystem services looks more like Fig. 1b than Fig. 1a, and that therefore the area *pbqc* is a conservative underestimate of the area *abc*. We then multiplied the unit values times the surface area of each ecosystem to arrive at global totals.

Ecosystem values, markets and GNP

As we have noted, the value of many types of natural capital and ecosystem services may not be easily traceable through well functioning markets, or may not show up in markets at all. For example, the aesthetic enhancement of a forest may alter recreational expenditures at that site, but this change in expenditure bears no necessary relation to the value of the enhancement. Recreationists may value the improvement at \$100, but transfer only \$20 in spending from other recreational areas to the improved site. Enhanced wetlands quality may improve waste treatment, saving on potential treatment costs. For example, tertiary treatment by wetlands may save \$100 in alternative treatment. Existing treatment may cost only \$30. The treatment cost savings does not show up in any market. There is very little relation between the value of services and observable current spending behaviour in many cases.

There is also no necessary relationship between the valuation of natural capital service flows, even on the margin, and aggregate spending, or GNP, in the economy. This is true even if all capital service flows had an impact on well functioning markets. A large part of the contributions to human welfare by ecosystem services are of a purely public goods nature. They accrue directly to humans without passing through the money economy at all. In many cases people are not even aware of them. Examples include clean air and water, soil formation, climate regulation, waste treatment, aesthetic values and good health, as mentioned above.

Global land use and land cover

In order to estimate the total value of ecosystem services, we needed estimates of the total global extent of the ecosystems themselves. We devised an aggregated classification scheme with 16 primary categories as shown in Table 2 to represent current global land use. The major division is between marine and terrestrial systems. Marine was further subdivided into open ocean and coastal, which itself includes estuaries, seagrass/algae beds, coral reefs, and shelf systems. Terrestrial systems were broken down into two types of forest (tropical and temperate/boreal), grasslands/rangelands, wetlands, lakes/rivers, desert, tundra, ice/rock, cropland, and urban. Primary

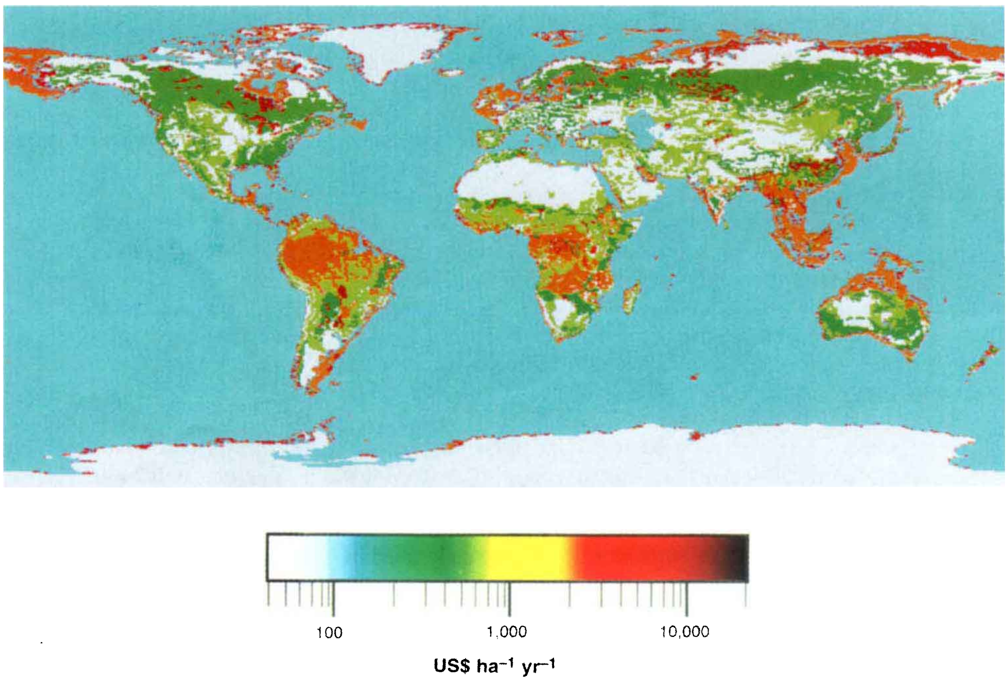

Figure 2 Global map of the value of ecosystem services. See Supplementary Information and Table 2 for details.

data were from ref. 17 as summarized in ref. 4 with additional information from a number of sources[18–22]. We also used data from ref. 23, as a cross-check on the terrestrial estimates and refs 24 and 25 as a check on the marine estimates. The 32 landcover types of ref. 17 were recategorized for Table 2 and Fig. 2. The major assumptions were: (1) chaparral and steppe were considered rangeland and combined with grasslands; and (2) a variety of tropical forest and woodland types were combined into 'tropical forests'.

Synthesis

We conducted a thorough literature review and synthesized the information, along with a few original calculations, during a one-week intensive workshop at the new National Center for Ecological Analysis and Synthesis (NCEAS) at the University of California at Santa Barbara. Supplementary Information lists the primary results for each ecosystem service and biome. Supplementary Information includes all the estimates we could identify from the literature (from over 100 studies), their valuation methods, location and stated value. We converted each estimate into 1994 US$ $ha^{-1} yr^{-1}$ using the USA consumer price index and other conversion factors as needed. These are listed in the notes to the Supplementary Information. For some estimates we also converted the service estimate into US$ equivalents using the ratio of purchasing power GNP per capita for the country of origin to that of the USA. This was intended to adjust for income effects. Where possible the estimates are stated as a range, based on the high and low values found in the literature, and an average value, with annotated comments as to methods and assumptions. We also included in the Supplementary Information some estimates from the literature on 'total ecosystem value', mainly using energy analysis techniques[10]. We did not include these estimates in any of the totals or averages given below, but only for comparison with the totals from the other techniques. Interestingly, these different methods showed fairly close agreement in the final results.

Each biome and each ecosystem service had its special considerations. Detailed notes explaining each biome and each entry in Supplementary Information are given in notes following the table. More detailed descriptions of some of the ecosystems, their services, and general valuation issues can be found in ref. 5. Below we briefly discuss some general considerations that apply across the board.

Sources of error, limitations and caveats

Our attempt to estimate the total current economic value of ecosystem services is limited for a number of reasons, including:
(1) Although we have attempted to include as much as possible, our estimate leaves out many categories of services, which have not yet been adequately studied for many ecosystems. In addition, we could identify no valuation studies for some major biomes (desert, tundra, ice/rock, and cropland). As more and better information becomes available we expect the total estimated value to increase.
(2) Current prices, which form the basis (either directly or indirectly) of many of the valuation estimates, are distorted for a number of reasons, including the fact that they exclude the value of ecosystem services, household labour and the informal economy. In addition to this, there are differences between total value, consumer surplus, net rent (or producer surplus) and $p \times q$, all of which are used to estimate unit values (see Fig. 1).
(3) In many cases the values are based on the current willingness-to-pay of individuals for ecosystem services, even though these individuals may be ill-informed and their preferences may not adequately incorporate social fairness, ecological sustainability and other important goals[16]. In other words, if we actually lived in a world that was ecologically sustainable, socially fair and where everyone had perfect knowledge of their connection to ecosystem services, both market prices and surveys of willingness-to-pay would yield very different results than they currently do, and the value of ecosystem services would probably increase.
(4) In calculating the current value, we generally assumed that the demand and supply curves look something like Fig. 1a. In reality, supply curves for many ecosystem services are more nearly inelastic vertical lines, and the demand curves probably look more like Fig. 1b, approaching infinity as quantity goes to zero. Thus the consumer and producer surplus and thereby the total value of ecosystem services would also approach infinity.
(5) The valuation approach taken here assumes that there are no sharp thresholds, discontinuities or irreversibilities in the ecosystem response functions. This is almost certainly not the case. Therefore this valuation yields an underestimate of the total value.
(6) Extrapolation from point estimates to global totals introduces error. In general, we estimated unit area values for the ecosystem services (in $\$ ha^{-1} yr^{-1}$) and then multiplied by the total area of each biome. This can only be considered a crude first approximation and can introduce errors depending on the type of ecosystem service and its spatial heterogeneity.
(7) To avoid double counting, a general equilibrium framework that could directly incorporate the interdependence between ecosystem functions and services would be preferred to the partial equilibrium framework used in this study (see below).
(8) Values for individual ecosystem functions should be based on sustainable use levels, taking account of both the carrying capacity for individual functions (such as food-production or waste recycling) and the combined effect of simultaneous use of more functions. Ecosystems should be able to provide all the functions listed in Table 1 simultaneously and indefinitely. This is certainly not the case for some current ecosystem services because of overuse at existing prices.
(9) We have not incorporated the 'infrastructure' value of ecosystems, as noted above, leading to an underestimation of the total value.
(10) Inter-country comparisons of valuation are affected by income differences. We attempted to address this in some cases using the relative purchasing power GNP per capita of the country relative to the USA, but this is a very crude way to make the correction.
(11) In general, we have used annual flow values and have avoided many of the difficult issues involved with discounting future flow values to arrive at a net present value of the capital stock. But a few estimates in the literature were stated as stock values, and it was necessary to assume a discount rate (we used 5%) in order to convert them into annual flows.
(12) Our estimate is based on a static 'snapshot' of what is, in fact, a complex, dynamic system. We have assumed a static and 'partial equilibrium' model in the sense that the value of each service is derived independently and added. This ignores the complex interdependencies between the services. The estimate could also change drastically as the system moved through critical non-linearities or thresholds. Although it is possible to build 'general equilibrium' models in which the value of all ecosystem services are derived simultaneously with all other values, and to build dynamic models that can incorporate non-linearities and thresholds, these models have rarely been attempted at the scale we are discussing. They represent the next logical step in deriving better estimates of the value of ecosystem services.

We have tried to expose these various sources of uncertainty wherever possible in Supplementary Information and its supporting notes, and state the range of relevant values. In spite of the limitations noted above, we believe it is very useful to synthesize existing valuation estimates, if only to determine a crude, initial magnitude. In general, because of the nature of the limitations noted, we expect our current estimate to represent a minimum value for ecosystem services.

Total global value of ecosystem services

Table 2 is a summary of the results of our synthesis. It lists each of the major biomes along with their current estimated global surface area, the average (on a per hectare basis) of the estimated values of the 17 ecosystem services we have identified from Supplementary Information, and the total value of ecosystem services by biome, by service type and for the entire biosphere.

We estimated that at the current margin, ecosystems provide at least US$33 trillion dollars worth of services annually. The majority of the value of services we could identify is currently outside the market system, in services such as gas regulation (US$1.3 trillion yr^{-1}), disturbance regulation (US$1.8 trillion yr^{-1}), waste treatment (US$2.3 trillion yr^{-1}) and nutrient cycling (US$17 trillion yr^{-1}). About 63% of the estimated value is contributed by marine systems (US$20.9 trillion yr^{-1}). Most of this comes from coastal systems (US$10.6 trillion yr^{-1}). About 38% of the estimated value comes from terrestrial systems, mainly from forests (US$4.7 trillion yr^{-1}) and wetlands (US$4.9 trillion yr^{-1}).

We estimated a range of values whenever possible for each entry in Supplementary Information. Table 2 reports only the average values. Had we used the low end of the range in Supplementary Information, the global total would have been around US$19 trillion. If we eliminate nutrient cycling, which is the largest single service, estimated at US$17 trillion, the total annual value would be around US$16 trillion. Had we used the high end for all estimates, along with estimating the value of desert, tundra and ice/rock as the average value of rangelands, the estimate would be around US$54 trillion. So the total range of annual values we estimated were from US$16–$54 trillion. This is not a huge range, but other sources of uncertainty listed above are much more critical. It is important to emphasize, however, that despite the many uncertainties included in this estimate, it is almost certainly an underestimate for several reasons, as listed above.

There have been very few previous attempts to estimate the total global value of ecosystem services with which to compare these results. We identified two, based on completely different methods and assumptions, both from each other and from the methods used in this study. They thus provide an interesting check.

One was an early attempt at a static general equilibrium input–output model of the globe, including both ecological and economic processes and commodities[26,27]. This model divided the globe in to 9 commodities or product groups and 9 processes, two of which were 'economic' (urban and agriculture) and 7 of which were 'ecological', including both terrestrial and marine systems. Data were from about 1970. Although this was a very aggregated breakdown and the data was of only moderate quality, the model produced a set of 'shadow prices' and 'shadow values' for all the flows between processes, as well as the net outputs from the system, which could be used to derive an estimate of the total value of ecosystem services. The input–output format is far superior to the partial equilibrium format we used in this study for differentiating gross from net flows and avoiding double counting. The results yielded a total value of the net output of the 7 global ecosystem processes equal to the equivalent of US$9.4 trillion in 1972. Converted to 1994 US$ this is about $34 trillion, surprisingly close to our current average estimate. This estimate broke down into US$11.9 trillion (or 35%) from terrestrial ecosystem processes and US$22.1 trillion (or 65%) from marine processes, also very close to our current estimate. World GNP in 1970 was about $14.3 trillion (in 1994 US$), indicating a ratio of total ecosystem services to GNP of about 2.4 to 1. The current estimate has a corresponding ratio of 1.8 to 1.

A more recent study[28] estimated a 'maximum sustainable surplus' value of ecosystem services by considering ecosystem services as one input to an aggregate global production function along with labour and manufactured capital. Their estimates ranged from US$3.4 to US$17.6 trillion yr^{-1}, depending on various assumptions. This approach assumed that the total value of ecosystem services is limited to that which has an impact on marketed value, either directly or indirectly, and thus cannot exceed the total world GNP of about US$18 trillion. But, as we have pointed out, only a fraction of ecosystem services affects private goods traded in existing markets, which would be included in measures such as GNP. This is a subset of the services we estimated, so we would expect this estimate to undervalue total ecosystem services.

The results of both of these studies indicate, however, that our current estimate is at least in approximately the same range. As we have noted, there are many limitations to both the current and these two previous studies. They are all only static snapshots of a biosphere that is a complex, dynamic system. The obvious next steps include building regional and global models of the linked ecological economic system aimed at a better understanding of both the complex dynamics of physical/biological processes and the value of these processes to human well-being[29,30]. But we do not have to wait for the results of these models to draw the following conclusions.

Discussion

What this study makes abundantly clear is that ecosystem services provide an important portion of the total contribution to human welfare on this planet. We must begin to give the natural capital stock that produces these services adequate weight in the decision-making process, otherwise current and continued future human welfare may drastically suffer. We estimate in this study that the annual value of these services is US$16–54 trillion, with an estimated average of US$33 trillion. The real value is almost certainly much larger, even at the current margin. US$33 trillion is 1.8 times the current global GNP. One way to look at this comparison is that if one were to try to replace the services of ecosystems at the current margin, one would need to increase global GNP by at least US$33 trillion, partly to cover services already captured in existing GNP and partly to cover services that are not currently captured in GNP. This impossible task would lead to no increase in welfare because we would only be replacing existing services, and it ignores the fact that many ecosystem services are literally irreplaceable.

If ecosystem services were actually paid for, in terms of their value contribution to the global economy, the global price system would be very different from what it is today. The price of commodities using ecosystem services directly or indirectly would be much greater. The structure of factor payments, including wages, interest rates and profits would change dramatically. World GNP would be very different in both magnitude and composition if it adequately incorporated the value of ecosystem services. One practical use of the estimates we have developed is to help modify systems of national accounting to better reflect the value of ecosystem services and natural capital. Initial attempts to do this paint a very different picture of our current level of economic welfare than conventional GNP, some indicating a levelling of welfare since about 1970 while GNP has continued to increase[31–33]. A second important use of these estimates is for project appraisal, where ecosystem services lost must be weighed against the benefits of a specific project[8]. Because ecosystem services are largely outside the market and uncertain, they are too often ignored or undervalued, leading to the error of constructing projects whose social costs far outweight their benefits.

As natural capital and ecosystem services become more stressed and more 'scarce' in the future, we can only expect their value to increase. If significant, irreversible thresholds are passed for irreplaceable ecosystem services, their value may quickly jump to infinity. Given the huge uncertainties involved, we may never have a very precise estimate of the value of ecosystem services. Nevertheless, even the crude initial estimate we have been able to assemble is a useful starting point (we stress again that it is only a starting point). It demonstrates the need for much additional research and it also indicates the specific areas that are most in need of additional study. It also highlights the relative importance of ecosystem services and the potential impact on our welfare of continuing to squander them. □

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The value of everything

Stuart L. Pimm

Economists and ecologists have joined forces to estimate the annual value of the services that Earth's ecosystems provide. Most services lie outside the market and are hard to calculate, yet minimum estimates equal or exceed global gross national product.

Economists' self-effacing definition of their craft is that it is one that knows the price of everything and the value of nothing. In that lies a crucial distinction.

Market prices are the easier objects of study, recorded abundantly in units (currencies) with known, if varying, calibrations. Values are more slippery, being likely to vary widely from person to person and from generation to generation. Prices, moreover, reflect incremental (or 'marginal') costs. Diamonds trade for a higher price than does fresh water. Yet the value of all fresh water is infinite: we could not survive without it. For ecologists, prices are woefully incomplete measures of nature's value that poorly prefigure the consequences of humanity's exponential growth. For economists, the challenge is how to assess an ecosystem's non-market values and predict their future trends. The words 'economics' and 'ecology' share a common root, yet for many years their practitioners had little to do with each other.

A turning point may have been C. W. Clark's 1973 demonstration that the most profitable strategy for harvesting whales is to convert all of them quickly into money in the bank[1]. Even the most stingy savings account produces interest income faster than whales reproduce themselves. Using the mutually intelligible medium of mathematical models, Clark's economics explained ecological history. Maximizing profits demanded that the slow-moving, inshore-feeding species were first hunted to extinction, before whalers tackled species whose capture required more advanced technology. The appropriately named right whales did go first, the 'wrong' whales following at ever shorter intervals. Generally, only species that grow faster than money in the bank should be harvested sustainably.

But if whales are more than just meat, how are we to estimate these other values? Trees in tropical forests grow slowly too: must economics doom them to extinction in the next century, like some whales in the last? On page 253 of this issue[2], a team of ecologists and economists, sponsored by the newly established National Center for Ecological Analysis and Synthesis in Santa Barbara, California, address such questions. Costanza *et al.*[2] take the flippant definition of economics to heart, estimating the annual value of all the world's ecosystems — essentially, the value of everything.

Take whales as an example. Whalers once set out from Lahaina and Nantucket on year-long trips armed with harpoons. Better-paid descendants set out on day-trips, escorting passengers armed with cameras. The cultural value of whales far exceeds that derived from their meat or oil, even if one only counts the price paid for boat tickets. Whales also have ecological roles that maintain species abundances of other marine species, including commercially valuable fisheries. These values, too, could be very large, and easy to estimate in theory, if not in practice.

Estimating other values is more contentious. Many people would consider Baker and Palumbi's observation[3] of the presence in Japan's sashimi trade of meat from the long-protected humpback whale to be a violation not only of international laws, but of religious principles, or to be evidence of unacceptable cruelty. Economists incorporate these views by asking how much the public would pay to protect whales. (A real example of such calculations involved asking how much the public felt deprived when the oil from the *Exxon Valdez* gummed up Alaska's scenically spectacular shoreline.)

Herein lies a vigorous debate, for others deem such calculations irrelevant — a feeble, last gasp of economists to fix their inability to assess real values. But would anyone accept child labour just because willingness-to-pay estimates for its abolition were smaller than the money saved by paying children less than adults? Aren't there overarching moral issues in placing monetary values on a sustainable environment for future generations? Costanza *et al.* point out that moral arguments make the discussions more difficult, but go on to say that they have no choice but to try to take them into account. In practice, we do indeed make financial trade-offs involving moral dilemmas, and the authors recommend that we proceed with both moral arguments and economic assessments.

Ecologists must grapple with exceedingly complex ecological interactions. Clear-cut a forest and the price of adjacent homes will

Estimating the cultural value of the oceans

Costanza and colleagues' summary table, Table 2 (page 256), is both fascinating and frustrating. Some numbers are small, others are huge. For none of them is there an indication of how they are obtained. How could there be in a journal with strict space limits? *Nature*'s Web site http://www.nature.com provides a solution that until recently would have been impossible: it displays the six-page spreadsheet and accompanying 18 pages of footnotes to document the calculations.

For example, how do the authors obtain a value of $76 per hectare for the cultural value of the world's open oceans? Multiplied across the planet's oceans this is a huge number – roughly $2.8 trillion. The tangible economic evidence of valuing the sea is how much more we will pay for coastal real estate than for comparable properties inland. (The calculation for the cultural value of coastal waters themselves is separate, and takes into account such factors as the scientific value of estuaries.)

For California, the difference between coastal and inland real estate is $10 million per hectare, for Alabama, only $500,000. Costanza *et al.* estimate the length of the coastlines of wealthy and less developed nations to be 194,435 km and 284,795 km, respectively, and assume coastal properties extend 0.5 km inland. They further assume that wealthy nations value their coasts 100 times as much as poorer ones, making the latter's contribution relatively tiny.

The total values come to $5-105 trillion, using the Alabama and California estimates, respectively. Amortized over 20 years, this yields the average value of $2.8 trillion, or $76 for each of the oceans' 36.3 billion hectares. All that is before we've added the money spent on tall ships (and yachts), the sextants to sight the stars to steer them by, and all the other paraphernalia needed to mess about in boats. **S. L. P.**

drop. The nearby streams will fill with sediment and lose their fish. Flowing to the sea, the sediment may smother the coral reef offshore, destroying its fish, beautiful corals, and the obscure invertebrate containing clues to the cure for cancer. The forest is a carbon sink. Its loss may accelerate global warming and sea-level rises. The coral reef may provide inshore areas with protection against storms. Costanza and colleagues' approach to these diverse services is to group them into 17 categories (the value of gas regulation, then climate regulation, through to cultural value) and to classify the planet's surface into 16 subdivisions or biomes. Then they proceed to estimate the 272 combinations one at a time. A summary of their valuations appears as Table 2 on page 256 of this issue, a much more detailed version being available as Supplementary Information on *Nature*'s Web site (see box on the preceding page for details).

Many combinations have yet to be estimated. Mountains, the Arctic and deserts certainly have cultural values and devoted eco-tourists, but these are absent from the grand total of \$33 trillion per year. Absent, too, are urban areas with city parks. A recent visit to New York's Central Park convinced me that children playing there appreciated its greenery, even if their parents living in the surrounding high-rise housing were too poor to own trees of their own. Filling in these and the other omissions will prove a rich training ground for graduate students in ecological economics.

Some of the numbers will be controversial. If the oceans were not there, re-creating their nutrient cycling would require removing the nutrients from the land's runoff and returning them. The estimate of this service's \$17 trillion value is arrived at by multiplying the cost of removing phosphorus and nitrogen from a litre of waste water by the 40,000 cubic kilometres of water that flow from the land each year (see Web site). It is geological cycles that return these nutrients. In the short term, many would not notice (and perhaps not care) what happens to the elements as they flow into the ocean. Even without this service, the remaining ecosystem services total \$16 trillion annually, a number to compare with the global GNP (gross national product) of \$18 trillion.

Parallel arguments for freshwater ecosystems are more immediate. We use fresh water directly and the function of natural ecosystems in waste treatment is large and frequently overlooked. Here the ecologists' intuition that current prices are a poor predictor of future value is self-evident. The price of an essential resource such as water will rise nonlinearly as it becomes scarce. We already use half of the available global supply of fresh water[4]. In some places, the situation is critical. Israel already uses more water than is available, taking the remainder from aquifers under the occupied West Bank, and off watersheds in the Golan Heights and southern Lebanon[5]. The region's population is increasing rapidly and its peoples have aspirations for a better life. The nonlinearities in the value of ecosystem services have political as well as economic consequences.

Table 2 on page 256 informs a strategic debate about why we should protect ecosystems. A powerful argument is that we should protect biodiversity as a potential source of new medicines and genes for crop improvement. Costanza *et al.*, quoting as-yet unpublished work by D. Pimentel, show that cultural and recreational uses of nature are even more valuable. Pimentel estimates the value of over-the-counter, plant-based drugs at \$84 billion annually, but eco-tourism at \$500 billion.

The real power of Table 2 lies in its use for local decisions. For example, a proposed project in southwestern Brazil and adjacent countries would straighten and deepen the rivers and so drain many of the surrounding wetlands — the Pantanal. The value of the increased quantities of soybeans that will be marketed is a simple calculation, but a grossly incomplete evaluation of the project's consequences. The Pantanal is an area that provides unusually high ecosystem services. Even if all the globally averaged benefits do not apply to this particular region, the global accounting provides a checklist for those who make difficult local decisions. Increasingly, such decisions will be informed by those who realize that there is more to a whale than its meat, and that wetlands, like all other ecosystems, provide services we cannot afford to replicate. □

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Geomorphology

When streams collide

Chris Paola

Dramatic effects can occur when two solid objects collide. The effects produced when two rivers collide are no less dramatic, but they are less familiar because they mostly happen under water.

The veil is lifted for one of the largest rivers in the world in the paper by Best and Ashworth on page 275 of this issue[1], which reports a sequence of bathymetric surveys in and around the confluence of the Jamuna and Ganges rivers in Bangladesh over a period of 28 months. They have discovered one of the mightiest natural scour holes ever described: about 30 m deep, some five times deeper than the channels feeding into it. Despite its great size, the scour is nimble: it migrated downstream at a mean rate of nearly 2 km per year over the measuring period.

There are several perspectives from which the size and dynamism of this impressive hole in the river bed are important. But first, why is the scour there, and how does it form[2–8]? Think of the confluence of two nearly parallel streams with different speeds. As the flows merge, the difference in speed gives rise to velocity shear and formation of the familiar line of vertical-axis vortices that one commonly sees in streams. In contrast, symmetrical confluences with more abrupt angles also produce vortices, but their axes are submerged and roughly flow-parallel (Fig. 1). So they are not obviously visible from the surface. The opposed components of momentum of the two colliding streams push the free surface of the water up in the neighbourhood of the junction and force a strong downwelling of water beneath the surface.

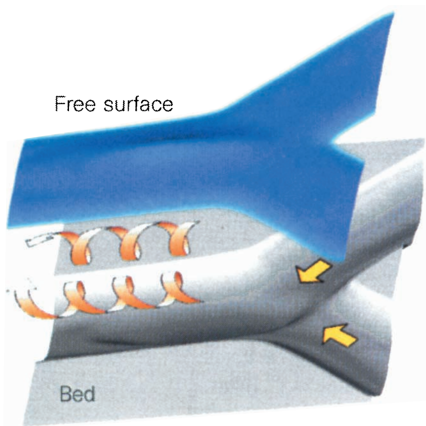

Figure 1 **Exploded, schematic view of the bed, flow pattern and free surface at a stream confluence. Collision of the two incoming streams raises the free surface and forces a downwelling flow along the boundary of the paired helical vortices, resulting in a deep scour on the bed and, as discussed here, a scour hole such as that identified by Best and Ashworth[1].**

As this downwelling water is driven sideways and back up again by the bed, all the while being carried downstream by the mean flow, it wraps back on itself to form a pair of powerful, counter-rotating vortices like those behind a twin-screw power boat. The downwelling region along the boundary of

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Ecosystem Services: How People Benefit from Nature

Rebecca L. Goldman

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ECOSYSTEM SERVICES: How People Benefit From Nature

by Rebecca L. Goldman

Erika Nortemann/© 2010 The Nature Conservancy

Paramo is the high altitude grasslands in the Northern Andes that help regulate water supply.

What do the blue jeans you wear, the hamburger you have for lunch, and the sheet you make your bed with have in common? They all take copious amounts of water to produce. One pair of blue jeans takes 2,900 gallons or about 78 bathtubs of water. Even your morning cup of coffee takes 37 gallons (about one bathtub) of water—not just the one cup you consume.[1] But we don't pay for all the water that goes into our morning cup of coffee. The price of the coffee is based on production and transportation costs (among other costs), but it's much more difficult to value where all the water in one cup of coffee comes from. This difficulty arises from the fact that natural ecosystems are responsible for the retention, release, and regulation of water, but how does a person value a natural ecosystem and the services it provides and put that into the cost of a cup of coffee?

Ecosystem services, or the benefits that nature provides to people,[2] have, in the past decade or two, become a growing focus for the conservation movement, both its science and its policy; see, for example, the Millennium Ecosystem Assessment,[3] the launching of The Ecosystem Marketplace (www.ecosystemmarketplace.com), DIVERSITAS (see http://www.diversitas-international.org), among many others. Uses and definitions of ecosystem services vary, but in general, ecosystem services help demonstrate the link between people and nature and the interdependence of our lives on ecosystem-based processes that create the products we need and use every day. Some examples of ecosystem services are water purification, water retention, soil fertility, carbon sequestration, and coastal protection, among many others.

What are some examples of how ecosystem services are already a part of our lives, how might ecosystem service considerations change daily decisions, and why is this behavior change important? In this article, I answer these questions using three examples—pollination services, flood and natural disaster protection services, and water services—to illustrate the interrelationship between nature and people. With each example

I provide a policy or personal decision-making context into which this link could be relevant and/or could lead to a different choice or behavior.

I do this for three reasons. First, I want to introduce the concept of ecosystem services in a more tangible way to demonstrate that ecosystem services are not just relevant to academics and conservation practitioners but to everyone. Second, I want to demonstrate the impact that behaviors and choices have on service provision. Finally, I want to underscore the importance of ecosystem services for a sustainable future and how, by fully considering the tradeoffs associated with daily choices, people can, with small changes, make a potentially large difference. I conclude by illustrating some programs, policies, and reports that have truly enveloped this approach and demonstrate the large impact the "ecosystem services movement" can have on our future. First, however, I begin with some general background about ecosystem services and their importance to sustainable development and to conservation.

Why Are Ecosystem Services Important for Sustainable Development?

The human population is expected to reach 9 billion people by 2050, and with that increase will come a greater demand for many natural resources. Look at freshwater needs, for example. Research has estimated per person per day dietary needs of 2,000–5,000 liters of water, and this does not include water needed for cleaning and other activities.[4] Hand in hand with this growing demand for resources is the conversion of native ecosystems to meet growing needs; this is where a tradeoff assessment in terms of ecosystem services might be useful.

Agricultural and pasture lands represent about 40 percent of global land surface.[5] If people continue to depend on agricultural products as they have in the past, then by 2050, scholars estimate that 10^9 hectares of natural ecosystems will be converted to agriculture. This conversion would include a 2.4–2.7-fold increase in nitrogen- and phosphorus-driven eutrophication of numerous waters with similar increases in pesticide use.[6] Agriculture already accounts for 70 percent of water withdrawals from lakes, rivers, and aquifers.[7]

This dependence and use pattern we have with our land is no different in the oceans. One clear example is oysters. Oysters have been consumed for sustenance for millennia. Reports from the 1800s in England indicate that in one year, 700 million European flat oysters were consumed, a process that employed about 120,000 people.[8] In the

iStockPhoto/ALEAIMAGE

Your morning cup of coffee takes 37 gallons (about one bathtub) of water to produce—not just the one cup you consume.

Chesapeake Bay on the Eastern Shore of the United States, oyster reefs used to extend for miles. By the 1940s, these reefs had largely disappeared.[9] This is, sadly, true of many ocean creatures, and it underscores our dependence on nature and how a growing demand can affect nature's ability to support itself and us.

We are at a critical juncture. Making choices that can benefit both us and nature may be our best option for securing our livelihoods. Ecosystem services provide a means for people to understand the link between their choices and the natural world. But what exactly are ecosystem services, and how does nature "create" these services? It is to the answers of these questions that I now turn.

What Are Ecosystem Services?

Underlying all the resources we use, the species we see, and the foods we eat are ecosystem processes: the biological, chemical, and physical interactions between components of an ecosystem (e.g., soil, water, species).[10] These processes produce benefits to people in the form of clean water, carbon sequestration, and reductions in erosion, among others. These benefits are ecosystem services.[11] The ability of nature to help filter, regulate the release of, and capture and store water allows us to wear blue jeans, drink coffee, and eat a hamburger, but we rarely think about the true origin of the products we use every day.

The distinction between ecosystem process, services, and goods is one that has received a lot of attention in the literature.[12] The key points emerging from these discussions are that ecosystem processes create our natural world. Ecosystem services are the link between this natural world and people, that is, the specific processes that benefit people. (There can be processes that are not services if there is no person to value that particular process.) Ecosystem goods are created from processes and services and are the tangible, material products we are familiar with, but again the distinction between goods and services is complicated and interrelated.[13]

The appeal of ecosystem services for conservation is the connection to people and people's well-being and how that appeal translates into new and increased interest in conservation across a wide range of resource management issues.[14] Ecosystem services can provide a means to value people's well-being in conservation projects and can help advance a set of on-the-ground actions that are equitable, just, and moral.[15] Ecosystem services can be a basis for sustainable development by providing a means to think through how to retain our natural resources for people and for nature with a growing population and therefore an ever-increasing demand for them.

Ecosystem services, since they are the benefits from *nature*, are often discussed in the context of conservation, but in our daily lives we make choices that depend on and affect flows of services from nature, since all goods and products we use today originate from nature and its services. Each choice we make—drive or ride a bus, buy organic or buy regular vegetables, turn on the heat or put on an extra sweatshirt—has tradeoffs. Conserving nature or converting nature does too, but tradeoffs associated with nature's values are often harder to assess. Not understanding nature's role in the products we use means we won't conserve nature sufficiently; this in turn will compromise our ability to access products we need, or we will have to find sometimes costly alternatives for what nature could otherwise provide to us. Incorporating the full suite of costs and benefits into decision-making means evaluating all costs and benefits associated with nature, too. Economists refer to this full valuation as shadow pricing, but even an informal, "back-of-the envelope" calculation of all values can help to illustrate the importance of ecosystem services in our daily lives.

Ecosystem services help connect people to nature and allow us to make more informed decisions by underscoring all the component pieces of the products we value. How might considering these multiple cost and benefit streams alter people's behaviors? How are people's daily choices linked to ecosystem services? I provide concrete examples to answer these questions.

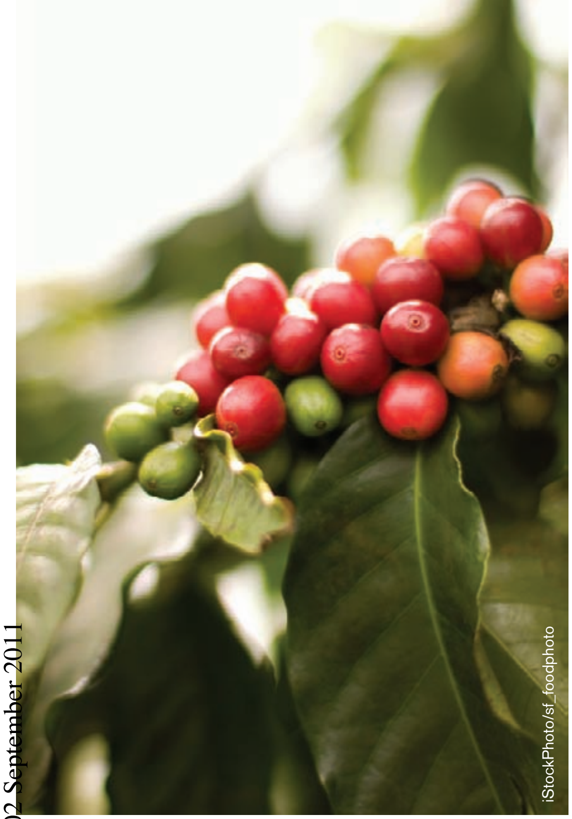
Agricultural and pasture lands represent about 40 percent of global land surface. If people continue to depend on agricultural products as they have in the past scholars estimate that by 2050, 109 hectares of natural ecosystems will be converted to agriculture.

How might ecosystem services change which products we purchase at the supermarket?

To provide a more tangible understanding of the behind-the-scene tradeoffs affecting choices we make, I will use the example of pollination services from native pollinators supported by natural ecosystems. In 2006, around the world there was a great deal of news and concern about the sudden and extreme disappearance of the honey bee, *Apis mellifera*,[16] due to colony collapse disorder (CCD). The disappearance of the honey bee would have catastrophic financial outcomes, since it is the most economically valuable pollinator worldwide.[17] About 90 percent of commercially grown field crops, citrus and other fruit crops, vegetables, and nut crops currently depend on honey bee pollination services. These crops in the United States are valued at $15–20 billion[18] and include Pennsylvania's apple harvest, which is the fourth largest in the nation with an estimated worth of about $45 million per year and California's almond harvest, which accounts for 80 percent of the world's market share of almonds.[19]

The honey bee most common in the United States is native to Europe, and many of the crops pollinated by honey bees today such as watermelon, almonds, blackberries, and raspberries, among others, could be pollinated by bees native to the landscape (often more efficiently), allowing an ecosystem to generate these important services rather than having to import honey bees from elsewhere.[20] Bees generally require food (flower pollen) and habitat (native vegetation) to survive in a landscape. In addition, bees do not fly great distances, so they require patches of native habitat they can easily fly between.[21] The good

About 90 percent of commercially grown field crops, citrus and other fruit crops, vegetables, and nut crops currently depend on honey bee pollination services that in some cases could readily be provided by native pollinators living in natural ecosystems.



The price of the coffee grown on farms like this one in Kona, Hawaii, is based on production and transportation costs (among other costs), but it's much more difficult to value where all the water in one cup of coffee comes from.

news is that studies have shown that retaining even small patches of native habitat provides native bees a home and best promotes pollination ecosystem services.[22] If, however, we can ship bees in to provide pollination, why should farmers or the general public care if we eliminate native landscapes and their native pollinators?

One good reason to care is that using nature to provide services can reduce costs for farmers,[23] since wild bee pollinators can be as efficient as managed bees.[24] Farmers wouldn't have to pay the costs of transporting and caring for honey bees to successfully produce their crops. In a coffee plantation in Costa Rica, for example, Ricketts et al.[25] found that services from wild pollinators living in native rainforest patches embedded in the coffee farm were worth $60,000/year, and this is just one service provided by the forest. Other services such as carbon sequestration, soil stabilization, flood mitigation, and water purification could also have added value for the farmer (soil stabilization), for other people in the region (water purification and flood mitigation), and for people around the world (carbon sequestration). Loss of this rainforest, thus, has equivalent costs to society. Yet, right now, despite the plethora of studies that demonstrate which farming practices can greatly impact native bee populations, either encouraging their survival or leading to their demise,[26] many coffee farms depend on the honey bee and not wild pollinators for crop production, making them very vulnerable to extreme consequences of honey bee decline.[27] Why?

The use of native pollinators for crop pollination is not ubiquitous, because this ecosystem service does not come without tradeoffs. Keeping patches of native vegetation on an agricultural landscape means less space for crop production and potentially a reduction in yield. Changing farming practices might mean changing machinery or learning new techniques, which can take time and might have other associated costs. As with any change in practice, there is a risk, and just as consumers have an incentive to buy the least costly vegetables in the market so they can save more money, farmers have an incentive to produce crops as cheaply as possible. Changes in practices sometimes include large, upfront costs that are not offset by benefits or not offset immediately enough, even if in the long run production costs are actually less.

As alluded to, there are tradeoffs associated with destroying native ecosystems and therefore eliminating pollination services. What if more crises occur such as the CCD outbreak leading to further loss of honey bees, and suddenly the cost of importing and keeping these bees becomes unsustainable? Keeping patches of natural ecosystems on the landscape can support a diversity of bee species, making pollinators less vulnerable to being completely annihilated by one disease. What if it would be cheaper to restore some cropland now to ensure some native pollinators are retained, since studies show native bee communities might be an insurance policy in the event of honey bee decline?[28] Who should have to pay for these costs? Should consumers pay $.50 more for a cup of coffee, for example, to help offset potential upfront costs to farmers for using ecosystem pollination services?

According to the soon to be released United Nations TEEB report, conserving nature and ecosystem services might be 10–100 times more valuable than the cost of saving the habitats and species associated with the provision of the services; this demonstrates the potentially major impact of including nature's values.[29] As consumers, it might cost us more at first to buy coffee pollinated by native bees, but in the long run it might be much less costly. This matters for policy, too. For example, should the U.S. farm bill provide financial incentives for farmers to continue growing crops as we do traditionally, or should it subsidize the same crops but provide additional incentives to farmers to restore patches of native habitat to secure native pollination services in appropriate cases? These types of questions not only get at the complexities associated with ecosystem services and how to extract their exact value (how do you know how much extra to charge on the cup of coffee?), but also underscore the importance of broadening our understanding of all the tradeoffs associated with our everyday choices.

How might ecosystem services save your life or affect the house you buy?

As with the food we buy in the market, the houses and property we buy may be more or less valuable depending on the impact we have on nature. Nature can provide services that help to mitigate or at least diminish some potentially catastrophic impacts from weather events. Perhaps the most recent and often discussed example of this is the value that mangrove ecosystems have in protecting against coastal flooding and storms. These protection services can enhance or detract from the value of coastal property, and in the case of severe storms like tsunamis, can help save people's lives.

Mangroves are coastal forest systems and make up about 0.4 percent of the world's forests. They are among the most endangered ecosystems on the planet, yet they are frequently cleared so people can make use of the space they occupy for rice paddies, shrimp farms, or other productive activities. Mangroves provide numerous ecosystem services to people, including nurseries for the young of about 30 percent of commercial fishes, coastal protection to prevent erosion and loss of coastal lands, carbon sequestration that helps to reduce the concentration of carbon dioxide in the atmosphere, waste processing, food production, recreation, and protection against large storm surges.[30] For example, a recent study[31] demonstrated that larger mangrove ecosystems led to significantly greater fish catches without having to increase fishing efforts.

The loss of protective ecosystem services from the natural ecosystems may actually mean the coastal home you just bought was vastly overpriced.

Perhaps one of the most significant, yet undervalued, services from mangroves is their ability to help reduce damage caused by tsunamis and tropical storms.[32] Das and Vincent[33] demonstrated that mangrove forests can save lives in the context of large storms like the tsunami of 1999. Even the minimal coverage of mangroves around coastal villages in India reduced the death toll by one-third Das and Vincent took the study one step further and estimated that the mangroves could have sold for about $67 million (total of 44,000 acres), but their value in terms of life saving services was at least $80 million. Prior to the tsunami, these life saving services may not have been valued, and the consequences could have been grave.

Coastal protection is another important ecosystem service provided by mangroves, which can have important implications for a more basic choice: whether or not to buy a house. Property values are assessed based on a wide range of factors including taxes, location, views, noise pollution, etc., but without factoring in ecosystem services, or the lack thereof, one might pay an inappropriate amount for a house. For example, coastal properties are often the most costly because they have lovely views. If the coastal areas have coral reefs or mangroves, this is no less true; however, through destructive fishing practices and/or overuse, many of these reefs and forests are being destroyed. What once may have been prime real estate right on the water is now a home that is threatened with destruction at any time since it can be easily flooded by a strong storm surge or the ground below it could erode away. The loss of protective ecosystem services from the natural ecosystems may actually mean the coastal home you just bought was vastly overpriced.

Again, the choices are not so black and white. Denying poor coastal communities' access to mangroves for income purposes has costs, just as preserving the mangroves has benefits for human lives. Tradeoffs must be evaluated, and the range of costs and benefits must be included, but without accounting for ecosystem services values, you can't be sure if you should buy the coastal home or if you should cut down the mangroves to be able to sell more fish. More broadly, governments can't assess what policies might be needed to secure the well-being of their citizens. For example, should the Philippine or Indian governments regulate mangrove cutting more stringently while channeling funds into providing incentives to poor coastal dwellers to compensate them for lost income and further decrease the threat to mangrove systems?

What do ecosystem services mean for the water you drink?

People rely on clean, regular supplies of water for survival, whether for drinking or for the production of other goods and services (agriculture, electricity, etc.). Water users have an incentive to find the lowest cost options for accessing clean water. Interestingly, nature may provide the lowest-cost, longest-term means of providing such water services. Conservationists are increasingly recognizing the value in thinking about these low-cost approaches for financing conservation. Demonstrating the links between nature and people is a way to

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Mangrove ecosystems, like this one in the Florida Keys, are some of nature's most effective protections against coastal flooding and storms.


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Water runs past a village in Parque Ecológico Cachaco in Amaguaña, Ecuador.

engage new stakeholders in conservation[34] and potentially find new ways to finance activities.

Increasing numbers of case studies and research studies are emerging about the benefits of payment for ecosystem service approaches as a means to finance conservation.[35] While there is still uncertainty about what factors are likely to contribute to successful ecosystem service projects,[36] these approaches continue to proliferate. Payments for watershed service projects make up a significant portion of implemented ecosystem services schemes (many others relate to carbon). These schemes often involve water users paying "suppliers" for the delivery of clean, consistent water supplies.[37] Using a payment for watershed services approach, called "water funds," developed by The Nature Conservancy (TNC) and several partners, I will provide a tangible example of an ecosystem services approach that has changed the way users are securing access to water.

Water funds are a public/private partnership focused around a long-term, sustainable finance source for conservation. The partnership determines how to fund conservation of the watershed in order to protect valuable biodiversity and to generate vital water services (namely a clean, regular supply of water) upon which large groups of downstream people depend. For context, water funds are proliferating throughout the Andean region of South America, particularly in Colombia and Ecuador though they are not only in this region. The headwaters of important rivers originate in higher altitude natural ecosystems (composed of native grasslands, páramo, and mixed forest) that serve as the hydrologic regulators for the entire water system.

The problems in these Andean systems are three-fold: growing populations of downstream users require increased flows of services, the natural ecosystems that provide the services are not sufficiently protected, and the human communities that threaten the natural ecosystems are poor and depend upon these ecosystems for their livelihoods. In addition, their land use practices can have their own consequences for service provision, as farming and ranching can lead to reduced water retention and increased water pollution. But, water services can't be preserved solely by keeping people out of the natural areas and restoring the working landscapes, as this would compromise many livelihoods. Using an ecosystem services framework, TNC and partners used the dependence of downstream people on the services provided by natural ecosystems and restored working landscapes to finance conservation and livelihood projects to secure water services sustainably.

In a water fund, water users voluntarily invest money in a trust fund, and the revenue (interest and sometimes part of the principal) from it is used to finance conservation projects in the watershed, which are decided upon by the public/private partnership of users and key stakeholders that oversee the fund. These projects take steps to address the needs of preserving natural ecosystems and maintaining the well-being of watershed communities. Activities and projects can include hiring community-based park guards to maintain the natural areas (to maintain the natural hydrologic regulation of the system, which helps maintain a regular base flow), protecting riparian areas (putting fences up to keep crops and cows away from river banks), revegetating riparian areas (to provide a natural filter for sediments and other pollutants), planting live tree fences to delineate property boundaries, and isolating/fencing off headwaters and steep slopes. These practices can have major impacts on water quality, on the timing and volume of water flows (particularly floods), on fires, and on freshwater biodiversity. One study demonstrated that just maintaining natural vegetation on the landscape can decrease sedimentation tenfold compared with converting the area to cropland.[38]

In a water fund, water users voluntarily invest money in a trust fund, and the revenue (interest and sometimes part of the principal) from it is used to finance conservation projects in the watershed ...

Such management is not without costs, however, and thus the water fund not only finances conservation management projects but also supports community projects to compensate for impacts on livelihoods. Ideally, conservation management activities will enhance farm/ranch productivity through the production of on-farm ecosystem services such as soil stabilization and enhanced soil fertility, but these benefits will not be immediate and are not guaranteed. In the shorter term, conservation management agreements include livelihood investments such as environmental education programs, additional income sources such as guinea pig farms, alternative food sources such as organic vegetable gardens, and expanded capacity for the production of goods such as providing communities with ovens to make the drying of fruit and herbs they sell on the market more efficient and effective.

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June 2010 – Pichincha Province, Ecuador. School children from Sangolqui participate in activities designed to teach them about the environment at Parque Ecológico Cachaco in Amaguaña. Administered by Fundacion Ecológica JASDUC, the park includes watershed restoration for the Río San Pedro.

The premise of water funds, therefore, is that securing natural ecosystems and improving management of farms and ranches in the watershed will help to ensure users have clean water available to them year round ...

In this case, taking an ecosystem services approach meant being holistic and recognizing that the downstream users of water have an incentive to find the lowest cost option for continued access to clean water and that nature can provide that service potentially more cheaply and for longer than built infrastructure. The premise of water funds, therefore, is that securing natural ecosystems and improving management of farms and ranches in the watershed will help to ensure users have clean water available to them year round, and in return for these services, users pay for the upstream conservation management. This approach has had tremendous replication success in this region of South America, with the implementation of seven water funds in the last decade serving cities with combined populations of over 11 million people and helping protect over 1.6 million hectares of land.[39]

How Are Ecosystem Service Approaches Being Leveraged?

The last five years have seen the proliferation of ecosystem services strategies, not just in on–the-ground actions but also in the emergence of new offices, new projects, and new strategies within conservation NGOs, governments, and multilateral donor agencies. This increased attention started with books such as *The New Economy of Nature*[40]and interdisciplinary scholarly investigations such as the *Millennium Ecosystem Assessment* (MA) demonstrating the ecosystem alternatives to resource problems. The MA was called for by the United Nations secretary general in 2000 as a way to assess the impact of ecosystem change on human well-being including a scientific assessment of how to increase the conservation and sustainable use of these ecosystems to secure well-being. Over 1,360 scholars worldwide collaborated on the study publishing the findings in five technical volumes and six synthesis reports (see http://www.millenniumassessment.org/en/index.aspx for more information).

The concept has now been integrated into funding criteria by donor agencies. The World Bank, for example, has an entire strategy dedicated towards developing payment for environmental services (see http://go.worldbank.org/51KUO12O50). In addition, one of the major donor programs of the World Bank, the Global Environment Facility (GEF), has developed a Scientific and Technical Advisory Panel (STAP) to provide guidance on the evaluation of environmental service projects that are seeking funding, since these types of projects are becoming increasingly popular for achieving development and conservation objectives (see http://stapgef.unep.org/resources/sg/PES). This attention from the development community is a clear link between ongoing conservation efforts and efforts to help enhance global development.

Beyond multilaterals, governments are also paying more attention to the benefits of nature to people. This attention may be best illustrated by the relatively recent formation of an entire office in the U.S. government's Department of Agriculture that is dedicated to catalyzing new markets for ecosystem services (see http://www.fs.fed.us/ecosystemservices/OEM/index.shtml). This Office of Environmental Markets was formed in 2008 and aims to help support farm bill programs in the U.S., which can have significant benefits for service provision throughout the country.

There is also a growing and rapidly evolving focus on ecosystem services by conservation nonprofits. Organizations such as Conservation International, TNC, and WWF are changing their missions and/or developing projects that focus on integrating people and nature.[41] New partnerships, notably, the Natural Capital Project—a partnership between Stanford University, TNC, and WWF—are being created to provide tools (see http://www.naturalcapitalproject.org/InVEST.html) to map the flow of various services in geographies around the world and to help more effectively include natural capital in decision-making.

Finally, there is recognition across government, particularly recently by the German Federal Ministry and the European Commission, with other partners, of the importance of making sure we include the true costs of lost biodiversity and associated ecosystem services on our future. In an effort to fully understand the benefits nature has for people's well-being, this group commissioned the TEEB report to sharpen awareness, help facilitate creation of cost-effective policies, and help make better informed decisions (e.g., see Jowit 2010).[42]

Over the next decade, measuring the impact of ecosystem service–based approaches both on people's well-being and also on nature is critical. Understanding which activities and actions yield a particular outcome and at what cost will provide us with a more evidence-based suite of options for making informed choices in our daily lives.

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Learning to Value Ecosystem Services

By: Sharon Kingsland

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The terms "ecosystem" and "Dust Bowl" coincidentally both entered the English language in 1935. Before then ecologists had focused on the study of plant and animal "communities," but British ecologist Arthur Tansley thought they were neglecting the surrounding earth, air, and water. He suggested that the word "ecosystem" better captured the connections between the living and nonliving worlds.[1] He did not have the Dust Bowl in mind when he did so, but the Dust Bowl, as the worst environmental disaster that modern Americans had ever experienced, is a stunning example of a collapse of natural infrastructure resulting in a loss of ecosystem services. Henry A. Wallace, secretary of agriculture at the time, warned that Americans had a duty to protect the soil to create a foundation for the nation's future.[2] The bad habits of overplowing, overgrazing, and overcutting of timber that brought on the Dust Bowl might be excusable in a young civilization, he declared, but not in the United States in 1938. Two generations later we express similar views of our debt to nature and duty to future generations when we assert the importance of protecting ecosystems so as to maintain "ecosystem services," or in other words, to maintain our life-support systems.

What is an ecological "system" and how has ecosystem ecology shaped our understanding of these beneficial "services"? Tansley's "ecosystem" term did not catch on right away, but it took on new meaning after the Second World War as ecologists grappled with new kinds of problems. By the 1960s the ecosystem concept had become a central ecological idea.[3,4] It dovetailed with the rise of systems thinking in other fields, for instance in cybernetics, a new science that studied feedback and control in any kind of system. A typical problem in cybernetics was how to guide missiles toward their targets. The cybernetic approach could also be applied to the behavior of organisms to explain how goal-directed behaviors are the result of physiological feedback mechanisms. By extension this approach could apply to larger groups of organisms that are linked ecologically through the food web, forming ecosystems.

When ecosystem ecology first emerged in the 1950s, many were doubtful of the value of this neologism. The two people most responsible for arguing that the ecosystem was a system in this cybernetic sense were Eugene P. Odum and Howard T. Odum, brothers who became leading ecosystem ecologists. They collaborated on one of the most successful ecology textbooks of all time, *Fundamentals of Ecology*, first published in 1953, which made the ecosystem concept the central organizing principle of ecology and emphasized the many applications of ecology to current problems.[5] Over the next two decades the concept assumed greater meaning as ecologists studied the "web of life" and filled in details about how systems worked.

The ecosystem perspective in ecology studied how materials, such as nitrogen, phosphorus, or carbon, moved back and forth between living and nonliving parts of the system, forming a cycle driven by energy from the sun, which was captured by photosynthesis. The value of the ecosystem concept as an organizing principle came from the way it focused attention on how multiple feedbacks between organisms and their environment resulted in stable natural systems. That is, ecosystems were stable because they were ecologically complex. When humans removed species and simplified ecosystems, they also made them less stable. The ecosystem perspective, in Howard Odum's view, provided a way of seeing the big picture: it was a macroscopic view of the world meant to identify the system's main features and to help figure out what preserved or destroyed its stability. The flip side of this focus on stability was the idea that ecosystems might collapse quite suddenly if they became unstable. The environmental debate that unfolded in the 1960s and 1970s placed great emphasis on preventing catastrophic collapse.

Ecosystem ecology was a science of the atomic age. With the development of atomic energy and the atomic bomb, radiation sources were becoming more numerous, and knowledge of the pathways of radiation and accumulation points for radiation in ecosystems was needed. Since we would be living in a world with increased radiation sources, it was important to understand how radioactive materials entered our diet through the food chain and whether they posed a health risk. As the national laboratories became centers for the development of atomic technology in the postwar period, they also became growth centers for ecosystem ecology. Much of the funding for ecological research came from the Atomic Energy Commission, and with this help Eugene Odum built a major center of ecology at the University of Georgia. The Odum brothers also studied coral reef ecosystems at bomb-testing sites in the Marshall Islands. By the 1970s ecologists were developing a much more sophisticated understanding of the many ways that ecosystems served as life-support systems for the inhabitants of “spaceship earth.”

These life-support systems endured for relatively long periods. Even with disturbances like fire, a healthy system could adjust and reestablish itself. If it could not adjust to normal disturbances, it was unhealthy. Usually humans were the cause of serious maladjustments and therefore humans came to be seen as pathogens or cancers, causing illness to the system or malfunction in nature’s machinery. The debates about overpopulation that came to dominate environmental discussions in the late 1960s and early 1970s, as exemplified by Paul Ehrlich’s polemic of 1968, *The Population Bomb*, also played up this image of human population growth as a cancer on the earth.

But exhorting people to stop reproducing for the sake of the planet’s health was not an effective solution. Calculating and explaining the value of natural systems to people seemed a better way to connect conservation to human self-interest. The concept of “nature’s services” or “ecosystem services” started to be more carefully articulated in the 1970s, and here too the Odum brothers led the way. As they explained, people commonly valued developed areas like cities and wanted to preserve them, but “cities need the protection of an adequate life support system, many elements of which [the] natural environment provides free of charge.”[6] Without natural “free” services, such as purifying water by filtering it through the ground, the expense of maintaining a desirable quality of life in a city would be prohibitive, and cities would go bankrupt if forced to pay the costs. In this way the Odums emphasized the need to see natural and built environments as connected. If the quality of the natural environment was degraded, the quality of the developed environment would also deteriorate. The feedbacks connecting the natural and social systems also had to be understood. The Odums realized that a vast amount of research was needed to get a more accurate reading of how the systems were functioning. However, they thought it was worth trying out these new concepts in urban planning, especially in places where public opinion and government already supported the goal of controlling development.

Wetlands were one type of landscape whose vital services were often unrecognized. In a study published in 1974, James Gosselink, Eugene Odum, and R. M. Pope drew attention to the need to protect tidal marshes that were “vulnerable to capricious development because many of the real values of the marshes are not recognized, or accrue some distance from the marsh itself.”[7] For lands in private ownership, they recommended devising a system that allowed owners of natural resources that were of value to society to receive a return in exchange for protecting lands from development. They also recommended a long-term strategy whereby lands that performed key life-support functions could be acquired and protected before land speculation drove up the market price. The devastating impact of Hurricane Katrina on New Orleans and its barrier islands in 2005, worsened by degradation of the coastal ecosystem due to overdevelopment on the Mississippi River, demonstrated the wisdom of thinking ahead and not waiting for disaster to strike.

Where the ecosystem services argument focused on the need to preserve natural ecosystems, an alternative argument placed greater value on technology, management, and human ingenuity. The notion that we could engineer our way toward complete control of nature, or toward solutions to environmental problems, was common in postwar reflections on the future and had various expressions. One militant form of this argument held that we were engaged in a war against nature and needed to eradicate pests in order to win the war.[8] Rachel Carson famously argued against this logic in 1962 in her exposé of pesticide overuse, *Silent Spring*. Her point was that we needed to control ourselves, not nature.

Another argument drew from agricultural experience, extolling our ability to restore degraded lands and even to manage wilderness. Walter Lowdermilk from the U.S. Department of Agriculture found Israel’s reclamation of damaged lands to be inspirational as a model for the development of arid and semiarid regions elsewhere.[9] R. Merton Love, agronomist and range scientist at the University of California, Davis, argued in 1970 that in time we would be able to manage wilderness much as we had learned to manage our agricultural systems.[10] His vision was of total human control over ecosystems, and he argued that the prevailing conservation ethos should be replaced with an active management ethos. Ecologists John P. Holdren, Richard W. Holm, and Paul Ehrlich countered that the faith in technology or management that Lowdermilk and Love evinced was unrealistically optimistic at best and dangerously misconceived at worst.[11] Israel was a special case and could not be a model for poorer nations, and Love's approach rashly ignored the possibility that "wilderness contains answers we have not yet learned to seek."[11]

Holdren and Ehrlich also worried that environmental debates in the 1970s were placing too much emphasis on solving acute problems, such as pollution, while neglecting other problems, in particular the loss of the "public service" functions of ecosystems.[12] In 1974 they argued that human impact on the earth's systems showed that humans were a global ecological force, and unless population and consumption slowed down we were heading for disaster. At the same time, studies of pollution damage also steered attention to the larger question of how ecosystems provided critical services, such as clean air and water, binding of soil, or regulation of climate. Walter E. Westman, ecologist at the University of California, Los Angeles, and economist W. David Conn made a study of the damage from air and water pollution caused by energy production in California. Their report took a broad look at how we are deprived of important ecosystem services when we interfere with ecosystem functions, while acknowledging that the scientific study of these services was in its infancy. In 1977 Westman summarized their findings in a cogent appeal to recognize the value of ecosystem services.[13] One of his conclusions bears repeating today: that the public needed to have "a clear idea of the benefits they obtain from nature in its undeveloped state" so that they could convey to their government representatives their desire to preserve nature and control development.

Despite the discussions of the 1970s, ecosystem services did not emerge as a central theme of environmentalism until the late 1990s, aided by such books as *Nature's Services: Societal Dependence on Natural Ecosystems*, edited by Gretchen Daily and published in 1997. A group of prominent ecologists and economists, led by Robert Costanza, one of Howard Odum's former PhD students, joined forces to estimate the value of 17 ecosystem services worldwide and came up with a conservative estimate that their value was at least equal to the global gross national product.[14,15] Daily and Katherine Ellison followed up with an international survey of recent efforts to determine the value of natural assets.[16] These efforts were meant to jolt policymakers and the public into awareness of the huge cost of ecological damage.

Daily explained that the idea for the first book emerged when a group of environmentalists started lamenting "the near total lack of public appreciation of societal dependence upon natural ecosystems."[17] Harold Mooney and Paul Ehrlich argued that, although there were a few precedents for the notion of ecosystem services (as far back as Plato), the public remained "sadly unaware" of the connection between human welfare and ecosystem services.[18] They blamed the education system, public media, and also professional ecologists who collectively had failed to get the message out. Environmentalists also deplored the way the environmental debate had unfolded over the past half century. The regrettable habit of pitting technological optimists against environmental pessimists, as if these were two diametrically opposed worldviews, was stalling progress. It was time to start presenting complex issues in a balanced way.[19]

Presenting things in a balanced way also means that democratic societies must make choices about when to preserve, when to manage, and what kinds of technological solutions might work. The issues are indeed complex and we return to the problem of educating the public about what it means to maintain ecosystem services. We cannot rely on catastrophes like the Dust Bowl or Hurricane Katrina to deliver a sharp reminder to mend our ways. This raises the question of where and how ecological education should be conducted.

The essays in Daily's volume focused on natural ecosystems, an understandable choice given the authors' fears that these might soon disappear. But while it is important to know that such natural systems provide crucial services and must be protected, most people live in urban environments. If public opinion is to be changed, the place to do it is in the city, where people can see and experience both loss and improvement of ecosystem services.

Changes do not have to occur on an ecosystem-sized scale to impart lessons. People who decide to plant trees or turn a vacant lot into a garden are experiencing restoration of ecosystem services, and if it's a poor neighborhood they will see their home values increase as a result of such greening efforts. In an area of Baltimore known as Reservoir Hill, a dedicated community has been working for six or seven years to improve a depressing environment of vacant row houses one block at a time.[20] Along the way, environmental education has been introduced in the local elementary school and recreation center, and the community has built partnerships with local businesses and religious institutions.

Baltimore's Parks and People Foundation, which works to create connections between the city's network of parks, also provides greening advice to communities and fosters communication among groups. Such community-based activities help people to understand what it means to think of the urban environment as an ecosystem.

Community-based activism can profoundly influence a society's approach to its environment. In Toronto, Canada, a group called Friends of the Spit has been working for years to protect an urban wilderness that arose quite by accident and then grew into a cause célèbre in the city. The "spit" in question is the Leslie Street Spit, a narrow peninsula jutting five kilometers into Lake Ontario in Toronto's east end.[21] This artificial peninsula has been built up since the 1950s from harbor dredging and construction landfill. As vegetation grew on the site, it attracted birds and other animals; over time people began to see the spit as an emerging wilderness area. In 1977 Friends of the Spit was founded to lobby for public access to the site and for its protection, even as it was still being used as a construction landfill. For years the group battled various development plans for the waterfront area, always maintaining that the best plan was to leave the spit alone. Their dedication paid off and today the park is lauded as a unique urban wilderness. With more than 300 species of birds it has been named an Important Bird Area by a global alliance called BirdLife International that seeks to conserve bird diversity worldwide.

One consequence of this decades-long effort was to challenge the prevailing view that a park should have a finished or unchanging look. The spit, as a work in progress, is instead a classroom for the study of ecological succession. As it evolves it teaches about changing ecological relationships, enabling visitors to experience biological diversity in a way that is impossible in a more managed park.

These urban dwellers in Baltimore and Toronto may not be sitting down with calculators to figure out the hidden value of a tree, bird, or butterfly, and they are not operating on the level of an entire ecosystem. But they are all getting a direct lesson that ecosystem services improve their lives. Exercises in civic activism also educate people about how to be effective advocates for better practices. Such activism and its results may seem too small to matter, but a recent analysis of how we should approach ecosystem services poses the question, "Can ecosystem services be maintained solely through global or large-scale environmental policies without regard to regional or local-scale policy making?"[22] Policymaking on the local scale implies a need for education that uses examples on the local scale as well.

Even small-scale experiments are opportunities to raise people's awareness of how improved ecosystem services can affect their health, well-being, and wealth, but the lessons need to be extracted. We need a recorder and observer along the lines of Jane Jacobs, author of the 1961 classic *The Death and Life of Great American Cities*, which opened many people's eyes to what makes cities great.[23] She walked around cities, analyzing what created a vibrant, healthy cityscape and what did not. There would be high educational value in observing the urban scene as Jacobs did, but with an emphasis on ecosystem services, showing how the transformations (good or bad) that are continually occurring in cities can be translated into ecological terms and related to people's well-being.

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