Technological Substitution and Augmentation of Ecosystem Services

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Outline

Augmenting Nature's Productivity as Technological Substitution Substitution Possibilities for Ecosystem Services Implementing Technologies to Replace or Extend Nature's Services Bibliography

Glossary

Ecosystem Services are the benefits that ecosystems provide human beings. They include critical provisioning services such as food, timber, fiber, fuel and energy, and freshwater; regulating services that affect or modify, for instance, air and water quality, climate, erosion, diseases, pests and natural hazards; cultural services such as fulfilling spiritual, religious and aesthetic needs; and supporting services such as soil formation, photosynthesis, and nutrient cycling. This chapter doesn't explicitly address supporting services; they are implicit in the ability of ecosystems to deliver the other services.

Technology includes tangible man-made objects or "hardware" (such as tools and machines) and humandevised intangibles or "software" (such as ideas, knowledge, programs, spreadsheets, operating rules, management systems, institutional arrangements, trade and culture).

Substitute (or replacement) technologies are technologies that wholly substitute for some facet or portion of goods and services that ecosystems provide for humanity.

Technological augmentation of ecosystem services is the increase, through technological intervention, in the production of goods and services that nature provides. By helping fulfill humanity's needs while limiting its direct demand on nature, such augmentation substitutes for natural inputs from ecosystems.

Augmenting Nature's Productivity as Technological Substitution

Nature once produced virtually every service, good or material that humanity used. It supplied all food, fiber, skins, water, and much of the fuel, medicines and building materials. Over time, human beings developed technologies to coax more of these services from nature, often at the expense of other species. Agriculture and forestry increased the production of food, fiber and timber. Human beings also developed animal husbandry, commandeering other species to serve their needs for a steadier protein diet, for fiber and skins for bodily warmth and protection, to do work on and off the farm, and to transport goods and people. Gradually at first but faster in the past century, technological substitutes were developed which reduced human demand met directly by nature's services. Thus synthetic fiber today limits human

demand on nature to provide for clothes, skins and leather; vinyl, plastics and metals reduce reliance on timber for materials; fossil fuels — themselves products of nature — and nuclear power reduce pressures on forests and other vegetation to provide humanity's energy needs; synthetic drugs reduce harvesting of flora and fauna for life-saving medicines; and fossil fuel powered machines and telecommuting increasingly substitute for animal and human power. Nevertheless, population and economic growth continues to increase aggregate demand for most ecosystem services, and the adverse impacts of substitutions may compromise many ecosystems' abilities to provide other services.

The term "technology" as used here includes tangible man-made objects or "hardware" (e.g., tools and machines) and human-devised intangibles or "software" (e.g., knowledge, programs, spreadsheets, operating rules, management systems, institutional arrangements, trade and culture) (Ausubel 1991; Goklany 2007). There is substantial skepticism, reinforced by the Biosphere 2 project's costly failure, about technology's ability to adequately substitute for ecosystem services (Ehrlich and Mooney 1983; Mooney and Ehrlich 1997; Daily et al. 1997; Hawken 1997). Nevertheless, the Millennium Ecosystem Assessment, for instance, acknowledges technology's role in helping meet human demand, particularly for provisioning services such as food, while recognizing that adverse impacts accompany these technologies (MEA 2005a, 2005b). Recognizing this, Palmer et al. (2004) suggest the use of "designer ecosystems" to reduce humanity's load on nature. Noting that designed ecosystems are imperfect ecological solutions and may not pass muster with many conservationists and ecologists, they recommend their use as part of a future sustainable world to mitigate unfavorable conditions through a "blend of technological innovations, coupled with novel mixtures of native species, that favor specific ecosystem functions" rather than as *full* substitutes for natural systems (Palmer et al. 2004).

Indeed, while technology may occasionally wholly substitute for nature's goods and services, it will more frequently enhance their production. Because augmentation of nature's productivity reduces humanity's direct demand on nature, it's appropriately viewed as substituting for natural inputs from ecosystems. That's the view adopted in this chapter.

Consider food production. Had global agricultural productivity been frozen at its 1961 level, then the world would have needed over 3,435 million hectares (Mha) of cropland rather than 1,541 Mha actually used to produce as much food as it did in 2002 (Goklany 2007: 161-163). Thus, technological innovation effectively substituted for over 1,894 Mha of habitat, rivaling the total land reserved worldwide for conservation. Thus arguably *in situ* conservation has been enabled largely through augmentation of nature's services by agricultural technology (Goklany and Sprague 1992).

Enhanced productivity was based substantially on increased pesticides, fertilizers, water and fossil fuel inputs. However, such practices can have significant environmental costs. Preference should be given to practices that balance higher yields with lower inputs of land, water and chemicals so that they 'save' more of the environment than they destroy. And so it should be with other technologies for substituting or augmenting nature's services. However, while technology can reduce humanity's demands on nature, it cannot replace and/or substitute for nature down to the last detail. Arguably, given nature's complexity, it couldn't replicate itself in every detail if the clock were to be rolled back and restarted.

This chapter will briefly identify some technologies that would augment or replace ecosystem services in order to reduce the direct human demand on nature. This identification is meant to be illustrative rather than comprehensive. This chapter will not, however, evaluate the net efficacy or desirability of listed technologies based on their costs, benefits and impacts on nature. Those issues are outside this chapter's scope.

Substitution Possibilities for Ecosystem Services

Table 1 contains a summary of various technologies that could enhance or substitute for nature's ecosystem services. The ecosystem services identified in this table are adapted from the Millennium Ecosystem Assessment (MEA 2005a: Table 1). The following provides details of some of the technological possibilities.

FOOD

<u>Crops</u>. Most food that humanity consumes today comes from technological augmentation of nature's services through agriculture. The earth's carrying capacity prior to agriculture has been estimated at 10 million people (Livi-Bacci 1992: 29). However, ecological footprint of its 6.3 billion people in 2003 was estimated to exceed carrying capacity by 23 percent (GFN 2006). Therefore, assuming these estimates are accurate, present-day agriculture has boosted carrying capacity by over two orders of magnitude.

The world's population is likely to expand and become wealthier by mid-century, increasing food demand. Ideally, future agricultural practices will deliver higher yields but with lower natural and synthetic inputs (i.e., land, water, pesticides, fertilizers and fossil fuels). Options include more intensive

agriculture using conventional breeding techniques, genetically modified (GM) crops, and precision agriculture. These three approaches can co-exist.

GM crops, in particular, have high potential for low input high yield agriculture that could produce more food per unit of land and water diverted to agriculture. Several GM crops are in various stages of development ranging from research to commercialization.¹ For example, soil and climatic conditions are frequently less than optimal for specific agricultural crops. Accordingly, bioengineered grains are being developed to tolerate such sub-optimal conditions (i.e., drought, water logging, salinity, iron-deficient soil, or soils that are too acidic, too alkaline or have excess aluminum). Similarly, staples — rice, maize, wheat, cassava, sorghum — are being bioengineered to resist biotic stresses such as insects, nematodes, bacteria, viruses, fungi, weeds, and other pests. Such crops ought to reduce pesticide usage. Spoilage-prone fruits (e.g., melons, papaya, and tomatoes} are being bioengineered to delay ripening, increase shelf-life and reduce post-harvest losses. And the list goes on.

By increasing food produced per unit of land, water, and chemical inputs, GM crops would maintain or increase yields while reducing environmental impacts associated with agricultural activities. Higher yields would also reduce habitat loss, landscape fragmentation, pressures on freshwater biodiversity, pesticide and fertilizer usage, and soil erosion which then improves water quality, and conserves carbon sinks and stores. It may also displace use of more toxic pesticides with less toxic and/or less persistent ones.

Notably, GM crops have been cultivated commercially since 1996 without any detectable effects on human health. Experience worldwide indicates that they have reduced pesticide usage, and increased yields and farmers' profits [see PEST REGULATION, below].

Food production per unit of land, water and chemical inputs can also be extended through precision agriculture which uses combinations of high and low tech monitors, global positioning systems, computers and process controllers to optimize the amount and timing of delivering the various inputs, based on the cultivar, soil and climatic conditions specific to the farm (Goklany 2007: 393).

<u>Livestock</u>. Both conventional and bioengineering techniques can also be applied to increase livestock productivity by improving feed crops or the livestock so they can utilize feed more efficiently and reduce nutrients excreted in their wastes. For example, lysine is an amino acid that improves protein utilization in animals. Therefore, lysine supplements or high lysine corn and soybeans improve livestock feed and

¹This chapter's discussions on biotechnology and GM technologies draw liberally on Goklany (2007: Chapter 9).

reduce overall demand for land needed to produce animal protein, perhaps by as much as three quarters. Similarly, improving utilization of phosphorus in feed reduces phosphorus in livestock excrement and, consequently, nutrient loadings in the environment. This could be facilitated by using bioengineered corn and soybean which are low in phytic acid and/or contain phytase, an enzyme that improves phosphorus utilization. Scientists have developed a transgenic pig which contains phytase in its saliva and excretes 75 percent less phosphorus. Finally, corn with high oil and energy content, and forage crops with lower lignin content would also increase feed utilization by livestock, thereby also reducing demand for land and water to sustain livestock.

<u>Capture Fisheries</u>. The annual worldwide catch of marine and freshwater capture fisheries was approximately constant between 1995 and 2004 (FAO 2006). But production from aquaculture — appropriately viewed as a substitute for capture fisheries — increased rapidly from 4 percent of total fisheries production in 1970 to 32 percent in 2004.

In 2005, half the marine capture fisheries stock groups monitored by FAO were fully exploited; onequarter were underexploited or moderately exploited; the rest were overexploited, depleted, or recovering from previous over fishing. Inland capture fisheries were also generally overexploited. Thus, the potential for maintaining production from capture fisheries is currently low (Worm et al. 2006; but see Beddington et al. 2007). Accordingly, although aquaculture is not a panacea (Naylor et al. 2000, 2005), it will probably expand to meet demand for fish and other seafood (Goklany 2007: 363-367). This can be aided by increasing production at fish hatcheries, developing GM strains that would use feed more efficiently or utilize plant-based feed, and developing methods to improve health of cultured species to reduce pre-consumption losses.

<u>Wildfood</u>. Although the provisioning aspect of this service could be met through cultivation, that may not entirely fulfill deep-seated cultural, aesthetic, and psychic needs associated with the rituals of hunting, gathering and consuming wildfood (see below).

TIMBER

There are several technologies that would substitute for or augment the production of timber. These include tried and true approaches such as increased utilization of harvested product to reduce wastage (e.g., through the manufacture of plywood and other engineered woods, or computer-controlled manufacture of veneers), using high yield tree crops developed through conventional techniques, meeting

demand via vinyl, plastics and other petroleum-derived materials (e.g., fiberglass for insulation, or synthetics for flooring) or inorganic materials (e.g., aluminum and steel for construction). It could also include resorting to bioengineered trees. For example, lignin in wood must be chemically separated from cellulose to make pulp used in paper production. Researchers at Michigan Technological University have bioengineered aspen trees with half the normal lignin:cellulose ratio which, moreover, could increase pulp production by 15 percent from the same amount of wood.

Also, future generations, conceivably more comfortable with computer screens, may abandon hard paper copy as reading and information storage media in favor of inorganic electronic media.

NATURAL FIBERS, FURS AND SKINS

Sixty percent of the global demand for fiber is now met through synthetic fibers (e.g., polyester, nylon, vinyl, acrylic) (Kuffner 2004). Moreover, cotton, wool, silk, flax, jute, hemp and coir, although nominally classified as natural fibers, are produced largely through agricultural technology. In addition, cotton, the most abundant natural fiber, is increasingly produced from GM varieties which currently occupy 40 percent of the world's cotton acreage (ISAAA 2006; UNCTAD 2007).

Synthetic fibers also substitute for natural furs and skins, reducing pressures to either harvest wild animals or maintain livestock for those purposes, thereby diminishing demand for land, water and chemical inputs that would otherwise be required to maintain that livestock.

FUEL AND ENERGY

Traditionally, humanity's fuel and energy services were mostly obtained from wood, dung, solar, wind and hydro power, occasionally supplemented by geothermal power. Since the Industrial Revolution the fuel mix has shifted toward fossil fuels (themselves products of nature) and, to a lesser extent, nuclear. Given the present state of energy technologies, current energy demand cannot be met with nature's traditional energy services. Fossil fuels can thus be viewed as imperfect and overused substitutes for nature's services that initially conserved habitat.

Because of climate change, efforts are now underway to reduce fossil fuel usage. These include greater emphasis on new renewable technologies (e.g., photovoltaics, advanced wind and solar power devices, crop-based biofuels); nuclear; broad improvements in energy efficiency; and more exotic solutions (e.g., hydrogen fuel cells, fusion). Land-intensive energy solutions (e.g., biofuels and solar energy) could, however, have unintended adverse consequences for ecosystems and species (Ausubel 2007). A case in point is forest conversion in Malaysia and Indonesia to produce palm oil to meet Europe's subsidized biodiesel demand, which threatens endangered orangutans and other species (Reuters 2007).

Cultivation of energy crops ((e.g., corn, soybean, and oil palm) threaten to reverse last century's reductions in cropland per capita which have helped almost stabilize total habitat lost to cropland (Goklany 2007). Also, because these crops feed both humans and livestock and, moreover, are used in numerous products, prices for milk, meat and other food products have escalated, jeopardizing post-World War II advances against global hunger. Food costs have increased by 50 percent in the past five years in some places (Blas and Wiggins 2007).

Just as for food, timber and fiber, biotechnology can make crop-based fuel production more efficient. Hybrid approaches combining biology and chemistry could further increase efficiencies.

TRANSPORTATION AND WORK

For millennia, human beings have relied on beasts of burden to transport themselves and their goods, till the soil, and do other heavy work. These ecosystem services, although overlooked by the Millennium Ecosystem Assessment, are still used in developing countries. However, on farms and in cities, machines, mainly fueled by fossil fuel driven internal combustion engines, are displacing oxen, mules and horses; today trucks and trains carry far more goods on the Silk Road than camel caravans. While increasing fossil fuel consumption, this has reduced habitat lost to cropland that would otherwise be required to maintain animals providing these services. In the early decades of the 20th Century, when the U.S. population was a third of what it's today, 35 Mha (or 25 percent of U.S. cropland) were devoted to producing feed for the millions of workhorses and mules used on and off the farm. Therefore, technology, by rendering this ecosystem service largely obsolete in rich countries, has enormously reduced their land (and water) diverted to agriculture (Goklany and Sprague 1992).

GENETIC RESOURCES

One of nature's critical services is providing access to its vast library of genetic resources, much of which, unfortunately, is not catalogued, and may be in danger of being lost. *Ex situ* technologies that can be used to preserve this information include gene banks, zoos, and botanical gardens. Copies of this information can be created, and access facilitated, through the use of polymerase chain reactions. Biotechnology can also aid conservation by helping propagate threatened, endangered, and, perhaps — *a la* Jurassic Park — even extinct species.

BIOCHEMICALS, MEDICINES, PHARMACEUTICALS

Any process, substance or quality that exists or is produced in or by a living organism can, in theory, be bioengineered into man-made crops. Armed with such traits, bioengineered crops can be used to produce medicines and vaccines in so-called GM "pharms", manufacture bioplastics, biodiesel and other biofuels, colored or other forms of processed cotton, and eliminate toxic and hazardous pollutants from soils and waters. Once a better understanding is gained about how precisely genes help manufacture various proteins and control various processes in nature, bioengineering may help develop products and confer traits with no natural analogs. Today's chemical, pharmaceutical and manufacturing factories may also be supplanted by bioengineered crops, bioreactors and biofactories, essentially substituting older risks with newer but, hopefully, lesser risks (Goklany 2007: 392).

Synthetic manufacturing techniques and processes can substitute for medicines that would otherwise have to be produced directly from natural products. For example, aspirin, perhaps the most used drug in the world, is a synthetic form of a chemical found in the leaves and bark of willow trees. Similarly, the cancer drug paclitaxel, a semi-synthetic substitute for Taxol, eliminated the need to harvest the Pacific yew tree for the cancer drug. According to one estimate it would take six 100-year old Pacific yew trees to treat one patient (Edwards 1996). The semi-synthetic process which initially used material from the more abundant European yew has now been refined to use plant cell cultures rather than plant parts (EPA 2004).

FRESHWATER QUALITY AND QUANTITY

Despite some skepticism regarding cost-effectiveness of freshwater substitutes (Dybas 2001), numerous technologies are available and used routinely worldwide to clean and purify water to enable its safe use and reuse. Unfortunately, such technologies are underused largely because institutional and cultural factors frequently preclude pricing water and charging consumers the water's replacement price. Consequently, surface waters are oversubscribed and ground water is overdrawn (MEA 2005a: 39).

In addition to desalination, which can be economically and environmentally expensive, several other technologies treat, purify, recycle and reuse water. They include chlorination, ultraviolet radiation, filtration, and chemical and biological treatment (including sewage treatment) to reduce or remove pathogens, nutrients, metals and other chemicals to make water safe for human, agricultural, industrial and other uses. Treatment facilities come in sizes ranging from those designed for individual households to those suitable for towns. Thus, the number of people with access to safe water and sanitation has never

been higher. Nevertheless 1.1 billion people still lack access to safe water while 2.6 billion lack adequate sanitation adding greatly to the global burden of disease (WHO/UNICEF 2004).

Other technologies can, in effect, also reduce human demand on freshwater. Agriculture accounts for 85 percent of human freshwater consumption globally. Increasing the efficiency of agricultural water use by one percent would, on average, increase water for other human and environmental uses by 5.7 percent.

Moreover there is significant scope for reducing water withdrawals for municipal and industrial purposes (NHDES 2007). Municipal (and household) consumption can be reduced through restricted-flow appliances (e.g., toilets, shower heads, washing machines), while industrial water use can be limited through the use of process changes or closed-loop water systems.

Finally, it may be possible to design ecological systems to freshen water for human consumption while also providing the rest of nature access to that water. Palmer et al. (2004) note that "designing' ecosystems goes beyond restoring a system to a past state, which may or may not be possible. It suggests creating a well-functioning community of organisms that optimizes the ecological services available from coupled natural-human ecosystems."

AIR QUALITY REGULATION

One of nature's services is to cleanse various air pollutants from the atmosphere. This can be aided by technologies such as chemical scrubbers for sulfur dioxide and nitrogen oxides, electrical and mechanical devices such as electrostatic precipitators and fabric filters to reduce particulate matter, combustion devices to oxidize chemicals such as carbon monoxide and organic compounds, or process changes such as switching to low-sulfur or no-lead gasolines. These technologies, which rich nations used successfully to reduce emissions for traditional air pollutants (which excludes greenhouse gases), are now being transferred to developing countries through knowledge transfers or trade in equipment. Consequently, developing countries are addressing environmental concerns earlier in their development cycle (Goklany 2007). For example, the U.S. started replacing lead-in-gasoline in 1975, when its GDP per capita was \$20,000 (in 2000 International dollars, adjusted for purchasing power), whereas India and China began addressing this before their GDP per capita reached \$3,500 (World Bank 2007, based on Goklany 2007).

CLIMATE REGULATION

One of nature's services is absorption and desorption of carbon dioxide, which helps regulate climate. However, increased fossil fuel usage and changes in land use and land cover have increased atmospheric CO_2 concentrations by over 25 percent since industrialization started.

Technologies to reduce atmospheric greenhouse gas concentrations include biological sequestration on land through plant growth, carbon capture from CO₂ sources with subsequent sequestration in oceans or in geological formations, and biological sequestration in oceans by stimulating the growth of plankton and other organisms through iron fertilization (USCCTP 2006). Only the first of these is currently economically feasible. Specific technologies include faster growing trees and vegetation, reduced nitrogen usage, and conservation tillage (see subsection on crops in FOOD and TIMBER, above, and EROSION CONTROL, below). Carbon capture is technically, but not economically, feasible, while oceanic and geological sequestration are still in the research and development phases. Their long term environmental consequences need further evaluation.

Proposals have been floated for other exotic geoengineering options (e.g., orbiting solar power stations, or climate modification through injection of sulfates into the stratosphere or covering large areas with reflective films). Their economic and technical feasibility and environmental impacts also need further analysis.

At local and, possibly, regional scales, some climate regulation can be achieved by modifying land cover and albedo (through planting trees and other vegetation, reducing paved surfaces, or painting rooftops). At much smaller scales, air conditioning and heating serve as energy-intensive substitutes.

EROSION CONTROL

Physical disturbance of the land's surface due to tilling, construction, or removal of vegetation can contribute to erosion. This reduces soil productivity and increases losses of carbon into the atmosphere. Because it increases sediment and any soil-associated pollutants, it also reduces water quality. Erosion can be reduced through agricultural practices that would enable low- or no-till cultivation (i.e., "conservation tillage"), maintaining ground cover through cover crops or crop residue, and avoiding or postponing cultivation or disturbance of erodible soils.

Conservation tillage can be facilitated through the use of herbicide tolerant (HT) crops. These crops — developed through either conventional breeding or bioengineering — are designed to tolerate various

herbicides, so that herbicide application rather than mechanical or hand weeding reduces the competition between weeds and economically valuable crops.

U.S. experience with genetically modified HT crops has generally been positive. In the U.S., soybean competes with over 30 kinds of weeds which, left unchecked, can reduce yields by 50-90 percent. However, a HT soybean engineered to be tolerant to a broad spectrum herbicide, glyphosate, helps farmers get rid of weeds more effectively using lower amounts of less toxic and less persistent pesticides (see PEST REGULATION, below). Other popular HT varieties include those developed for corn, canola, cotton and alfalfa (ISAAA 2006).

DISEASE REGULATION

Nature regulates disease through various mechanisms. It provides habitat both for vectors that convey pathogens that might affect human beings, their livestock, and wildlife, and for the pathogens themselves. It also harbors organisms that prey on the vectors, such as "mosquitofish" that eat the larvae of mosquitoes that spread West Nile virus (Morse 2007). [See PEST REGULATION, below.] Substitute technologies include treatment or removal of habitat harboring the vectors, (e.g., by draining swamps, ponds or containers that could hold standing water), segregating vectors from human hosts or targets (e.g., by using insecticide-treated bed nets, screens on doors and windows, or insecticides to repel or kill vectors) (Grieco et al. 2007). Appropriate water treatment (e.g., chlorination) would also reduce water-related diseases such as dysentery and diarrhea. Finally, any incidences of disease could be treated with medicines.

PEST REGULATION

Substitutes for nature's pest regulation include the use of pesticides and control of habitat that pests need. Also, nature itself can be harnessed in integrated pest management.

A relatively new technology for controlling pests is to bioengineer crops to contain their own pesticides. GM crops that are resistant to viruses, weeds, insects and other pests have been developed. This should reduce pesticide usage, and their residues in the environment. Real world experience so far bears out this theory.

The most widely used crops containing their own pesticides use genes from *Bacillus thuringiensis* (Bt), a soil bacterium, which has been used as a spray insecticide in conventional agriculture for decades. Bt

varieties exist for corn, cotton, potato and rice. In the U.S., such crops are sometimes used as part of integrated pest management systems in which the Bt crop farmers plant refugia with non-Bt crops to retard the development of resistance in pests targeted by the Bt crops. They also should monitor the situation, which enables adaptive management. Other strategies include crop rotation, developing crops with multiple toxin genes with each toxin targeting different sites within the target species, and inserting the bioengineered gene into the chloroplast since that ought to express Bt toxin at higher levels.

Field studies from Arizona, Mississippi, Australia and China indicate that these strategies have effectively retarded evolution of resistant pests. In 2004, Bt cotton — planted on 7.1 million acres (or 51 percent of U.S. cotton area) — reduced pesticide use by 1.76 million pounds, increased yields by 82 pounds per acre, and netted farmers \$42 per acre (Sankula et al. 2005: 4-5). Insecticide runoff in a watershed before and after introduction of Bt cotton showed that pesticides that are most toxic to humans, birds and fish decreased between one-third and two-thirds (EPA 2001: IIE36). After Bt cotton adoption, bird counts increased by10 percent for Texas to 37 percent for Mississippi (relative to the pre-adoption situation; EPA 2001: IIE38-40). Elsewhere, Bt cotton helped China reduce pesticide use in 2001 by 25 percent below mid-1990s levels (Pray et al. 2002) and, during the 1999/2000 season, South African farmers who adopted Bt cotton had 60 percent higher yields and 38 percent lower pesticide consumption than non-adopters (Ismael et al. 2001).

Similarly, the use of GMHT soybean, canola, corn and cotton in 2004 reduced U.S. pesticide usage in 2004 by an estimated 55 million pounds (in terms of active ingredients) while increasing farmers' net income by \$1.8 billion (Sankula et al. 2005).

POLLINATION

Pollination is an important service that improves the quantity and quality of many agricultural crops such as apples, almonds, melons, blueberries, strawberries and alfalfa. In nature, some pollination occurs through the action of abiotic processes such as wind and water, but most is accomplished via insects (e.g., bees, butterflies, and wasps), birds, and bats. For some crops, e.g., apples, almonds, and blueberries, pollination has long been a managed activity with bee colonies being transported from location to location to coincide with the flowering season. In other words, managed pollination is itself the product of technology. In the United States, managed pollination is generally accomplished using European honeybees, a non-native species. Cultured insects, e.g., bumblebees for greenhouse tomatoes, or alfalfa leafcutter bees for alfalfa, may also be employed. Other technological substitutes include mechanical or hand pollination for small-scale applications such as greenhouses and small garden plots. The need for

pollination management has increased, possibly because some monoculture crops are insufficiently attractive to native pollinators, declining abundance of native pollinators, increasing size of monoculture plots, and the fact that some crops, being non-native, lack native pollinators.

NATURAL HAZARD MANAGEMENT

While nature is responsible for many hazards such as floods, hurricanes, tornados, drought, other extreme weather and climatic events, tsunamis, earthquakes, volcanic eruptions and other geological hazards, it also helps buffer some of their effects. Soils store large quantities of water, mediate transfer of surface water to groundwater, and prevent or reduce flooding while barrier beaches, coastal wetlands, mangroves and coral reefs help absorb storm surges from hurricanes and other wave action (MEA 2005a: 118). Although some of these services have been compromised because natural buffers have frequently been modified, if not eliminated, and human beings continue to place themselves and their property increasingly in harm's way, global mortality and mortality rates from extreme weather events have declined by 95 percent or more since the 1920s. The largest declines were for droughts and floods, which were responsible for 95 percent of all 20th century deaths caused by extreme events. For the U.S., current mortality and mortality rates due to extreme temperatures, tornados, lightning, floods and hurricanes also peaked a few decades ago (Goklany 2006).

These empirical trends suggest that notwithstanding any increase that may have occurred in frequencies and intensities of extreme events, technological substitutes have more than offset any losses in nature's protective services, at least with respect to protecting human lives. Declines in mortality are probably due to increases in societies' collective adaptive capacities owing to a variety of interrelated factors — increases in wealth, technological options, and human and social capital.

Technological options range from early warning systems and more accurate meteorological forecasts to artificial or restored wetlands and mangroves to defensive structures (e.g., dams, sea walls, levees, dykes) to better and smarter construction (e.g., stronger building codes, concrete and steel houses, houses built on stilts, floating structures; Hundley 2006), to improved communications and transportation systems which enables transport of men and materiel (including food, medical and other essential supplies) in and out of disaster zones, and to the 24/7 media coverage when extreme events seem imminent.

Experience with the 2003 European heat wave and Hurricane Katrina indicates that human and social capital are as important as technological options and greater wealth. Moreover, society's greater adaptive capacity to cope with extreme events and their aftermath must be deployed more rapidly and fully. The

consequences of failure of natural barriers may be less than that of poorly deployed technology-based adaptations.

SPIRITUAL AND RELIGIOUS VALUES

Nature also helps many individuals, communities and cultures fulfill spiritual and religious needs. However, such services are cultural constructs, inseparable from human beings. Much of this probably reflects a time when nature directly provided virtually all of humanity's provisioning services and was, therefore, endowed with — for lack of a better word —"supernatural" powers. Historically, objects such as paintings, sculptures, and relics helped satisfy, to some extent, religious needs that may otherwise have had to be met by undertaking arduous and dangerous journeys to distant places. But it's almost unimaginable that such objects or their modern-day counterparts — photographs, videos, movies, DVDs, holography — can be other than weak substitutes. Nevertheless, nature may, conceivably, be viewed with less reverence in the future, if technology further increases its role in displacing or augmenting nature's provisioning services, thereby diminishing demand for its spiritual and religious services.

AESTHETIC VALUES, RECREATION AND ECOTOURISM

Manmade or human-modified landscapes and ecosystems may also partially fulfill aesthetic, recreation and ecotourism needs provided by nature. A query for manmade sites in the Ramsar Sites database returned 514 hits (out of a total of 1675 sites) (RSIS 2007). A particularly successful example of a manmade ecosystem is India's Keoladeo National Park, also known as the Bharatpur Bird Sanctuary. This wetland — both a Ramsar Site and a World Heritage Site — protects the village of Bharatpur from frequent floods and provides grazing for cattle while also serving as habitat for 366 bird species, 379 floral species, 50 species of fish, 13 species of snakes, 5 species of lizards, 7 amphibian species, 7 turtle species, and a variety of other invertebrates (WWF-India, no date). Other man-made systems include lakes and reservoirs created behind dams and other water projects such as the Anaivilundawa Sanctuary in Sri Lanka, Lake Mead in the U.S.; and Lake Kariba in Africa. Clearly, although such water projects fulfill one set of demands for ecosystem services (e.g., water for drinking, agriculture, recreation and tourism), by diverting water, they also undermine the ecosystem's ability to meet other demands.

Human-augmented ecosystems include the Ranthambore National Park (and Tiger Preserve) in India, and manmade watering holes in Chobe National Park in Botswana. Other man-made or human-modified landscapes that partially substitute for nature range from the suburban gardener's backyard to Frederick Law Olmstead's Central Park in New York to England's rural landscape from farms to hedgerows. They may also include zoos and botanical gardens, as well as artificial reefs. Just as an Ansel Adams photograph, an Albert Bierstadt painting or a National Geographic DVD may, for some people, compensate for the real experience of visiting Yosemite, the Rocky Mountains or the Everest, so might the aesthetic services that nature provides be substituted through other paintings, photographs, high definition or, possibly, holographic television, videos, and movies. It should be possible, for instance, to take high definition virtual IMAX tours of coral reefs or nature preserves in the Caribbean, the Galapagos, or in Gombe. Similarly, one may in the future indulge in a virtual white water rafting trip down the Colorado, a hot air balloon ride over Victoria Falls, or a bicycling tour through the Swiss Alps.

Implementing Technologies to Replace or Extend Nature's Services

There are numerous technological options for replacing or extending the goods and services that ecosystems provide humanity. Generic options, particularly applicable to provisioning services — food, timber, natural fiber, energy — include technologies that would increase harvested yield per unit of land and water, increase utilization of harvested products through reductions in post-harvest and end-use losses, and enhance recycling (Goklany 1998).

Such technologies would reduce humanity's burden on nature, a burden that will otherwise increase as the global population increases and becomes wealthier. But these technologies often have severe environmental consequences. Accordingly, the trade-offs and synergies involved in meeting human needs and conserving the biosphere should be evaluated before implementing these options. Such evaluations, which necessarily should be done on a case-by-case basis, should also consider the effects of forgoing these technological options because in a complex and imperfect world there may be no perfect solutions (Goklany 2007: chapter 9).

Service	Product	Technologies or Technological Systems
PROVISIONING SERVICES		
Food	crops	high yield agriculture, precision agriculture, GM crops
	livestock	cloning, breeding, artificial insemination, GM animals, fortified feeds, high lysine feed
	capture fisheries	aquaculture, fish hatcheries, genetically modified fish, crop-based feeds
	wild foods	agriculture
Timber	wood	high yield tree crops, GM trees, aluminum, steel, plastics,
Natural fiber	cotton, silk, jute, flax, coir, hemp	synthetic fibers, plastics
	furs, skins	synthetic fibers
Fuel	wood, hydropower, wind	fossil fuels, photovoltaics, higher efficiency wind and solar, geothermal, nuclear, high yield biofuel crops, cellulosic ethanol
Transportation and work	beasts of burden	bicycles, mechanized transport (i.e., trucks and cars), airplanes, tractors
Genetic resources		polymerase chain reaction, gene banks, zoos, botanical gardens
Biochemicals, medicines, pharmaceuticals		synthetic drugs and pharmaceuticals, GM pharms, biofactories
Fresh water		Water purification and treatment, recycling and reuse technologies, desalination, water pricing and marketing, property rights for water
REGULATING SERVICES		
Air quality regulation	Traditional air pollutants	scrubbers, fabric filters and electrostatic precipitators for traditional air pollutants; emissions trading;
Climate regulation at local, regional and global scales		carbon sequestration on land, oceans, geologic formations; conservation tillage; geoengineering; modification of land cover and albedo
Water regulation		water purification and treatment, recycling and reuse technologies, desalination, water pricing and marketing, property rights for water
Erosion regulation		no- or low-till agriculture, hydroponic cultivation, cover crops
Water purification and waste treatment		chlorination, waste water treatment, filtration, reduction in oxygen demand
Disease regulation		chlorination, drugs and pharmaceuticals, insecticides
Pest regulation		insecticides, integrated pest management, GM crops
Pollination		Managed pollination via non-native/cultured pollinators (e.g., European honeybee in the US), hand/mechanical pollination, electrostatic enhancement
Natural hazard regulation		Artificial or restored wetlands and mangroves, dams, sea walls, levees, dykes, concrete and steel houses
CULTURAL SERVICES		
Spiritual/religious values		Photographs, movies, videos, HD and holographic television, virtual reality
Aesthetic values, recreation and ecotourism		Man-made or augmented landscapes and ecosystems, artificial reefs, zoos, arboretums, photographs, movies, videos, HD and holographic television, virtual tourism

Substitution Possibilities for Provisioning, Regulating, and Cultural Ecosystem Services

NOTE: Most substitutes are imperfect, and some more than others, however they provide products that would otherwise come from nature.

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