Untangling the Environmentalist's Paradox: Why Is Human Well-being Increasing as Ecosystem Services Degrade?

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Environmentalists have argued that ecological degradation will lead to declines in the well-being of people dependent on ecosystem services. The Millennium Ecosystem Assessment paradoxically found that human well-being has increased despite large global declines in most ecosystem services. We assess four explanations of these divergent trends: (1) We have measured well-being incorrectly; (2) well-being is dependent on food services, which are increasing, and not on other services that are declining; (3) technology has decoupled well-being from nature; (4) time lags may lead to future declines in well-being. Our findings discount the first hypothesis, but elements of the remaining three appear plausible. Although ecologists have convincingly documented ecological decline, science does not adequately understand the implications of this decline for human well-being. Untangling how human well-being has increased as ecosystem conditions decline is critical to guiding future management of ecosystem services; we propose four research areas to help achieve this goal.

Keywords: ecosystem services, human well-being, time lags, sustainability, adaptation

Although many people expect ecosystem degradation to have a negative impact on human well-being, this measure appears to be increasing even as provision of ecosystem services declines. From George Perkins Marsh's *Man and Nature* in 1864 to today (Daily 1997), scientists have described how the deterioration of the many services provided by nature, such as food, climate regulation, and recreational areas, is endangering human well-being. However, the Millennium Ecosystem Assessment (MA), a comprehensive study of the world's resources, found that declines in the majority of ecosystem services assessed have been accompanied by steady gains in human well-being at the global scale (MA 2005). We argue that to understand this apparent paradox, we need to better understand the ways in which ecosystem services are important for human well-being, and also whether human well-being can continue to rise in the future despite projected continued declines in ecosystem services. In this article, we summarize the roots of the paradox and assess evidence relating to alternative explanations of the conflicting trends in ecosystem services and human well-being.

The environmentalist's expectation could be articulated as: "Ecological degradation and simplification will be followed by a decline in the provision of ecosystem services, leading to a decline in human well-being." Supporters of this hypothesis cite evidence of unsustainable rates of resource consumption, which in the past have had severe impacts on human well-being, even causing the collapse of civilizations (e.g., Diamond 2005). Analyses of the global ecological footprint have suggested that since 1980, humanity's footprint has exceeded the amount of resources that can be sustainably produced by Earth (Wackernagel et al. 2002). Although the risk of local and regional societies collapsing as a result of ecological degradation is much reduced by globalization and trade, the environmentalist's expectation remains: Depletion of ecosystem services translates into fewer benefits for humans, and therefore lower net human well-being than would be possible under better ecological management.

By focusing on ecosystem services—the benefits that humans obtain from ecosystems—the MA set out specifically to identify and assess the links between ecosystems and human well-being (MA 2005). The MA assessed ecosystem services in four categories: (1) provisioning services, such as food, water, and forest products; (2) regulating services,

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which modulate changes in climate and regulate floods, disease, waste, and water quality; (3) cultural services, which comprise recreational, aesthetic, and spiritual benefits; and (4) supporting services, such as soil formation, photosynthesis, and nutrient cycling (MA 2003). Approximately 60% (15 of 24) of the ecosystem services assessed by the MA were found to be in decline. Most of the declining services were regulating and supporting services, whereas the majority of expanding ecosystem services were provisioning services, such as crops, livestock, and fish aquaculture (table 1). At the same time, consumption of more than 80% of the assessed services was found to be increasing, across all categories. In other words, the use of most ecosystem services is increasing at the same time that Earth's capacity to provide these services is decreasing.

The MA conceptual framework encapsulated the environmentalist's expectation, suggesting tight feedbacks between ecosystem services and human well-being. However, the assessment found that aggregate human well-being grew steadily over the past 50 years, in part because of the rapid conversion of ecosystems to meet human demand for food, fiber, and fuel (figure 1; MA 2005). The MA defined human well-being with five components: basic materials, health, security, good social relations, and freedom of choice and actions, where freedom of choice and actions is expected to emerge from the other components of well-being. Although the MA investigated each of the five components of well-being at some scales and in relation to some ecosystem services, the assessment of global trends in human well-being relied on the human development index (HDI) because of a lack of other data. The HDI is an aggregate measure of life expectancy, literacy, educational attainment, and per capita GDP (gross domestic product) that does not capture all five components of well-being (Anand and Sen 1992).

What we refer to as the environmentalist's paradox—namely, "How is it that human well-being continues to improve as ecosystem services decline?"—is an entry point to exploring the causal relationships between the biosphere and human well-being. Although there is overwhelming evidence that humanity has substantially changed the biosphere through biotic homogenization, climate change, and land-cover change (MA 2005, IPCC 2007, Kareiva et al. 2007), the consequences of these changes for human well-being are far less clear. In this article, we synthesize ideas from existing literature and use global data sets to assess four possible explanations of the environmentalist's paradox. We use this assessment to explore how human well-being is likely to be affected by ecosystem degradation in the future, and to determine what scientists need to understand better about this relationship if we are to manage it effectively.

Alternative explanations of the environmentalist's paradox

We present four hypotheses that may explain the environmentalist's paradox, each of which is founded in a synthesis of scientific discussions about human well-being, ecosystem dynamics, and natural resource management (table 2). These are just four out of many plausible theories. We synthesized these four to represent major lines of discussion on the topic of ecosystem services and human well-being. Although we present the alternative explanations as individual hypotheses, they are not mutually exclusive.

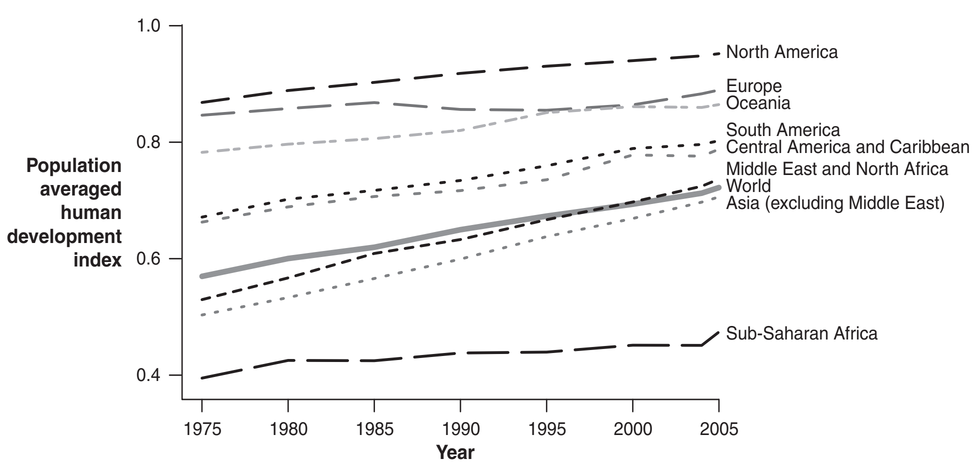

Figure 1. Human development has increased globally and within all the world's major regions over the past 35 years (UNDP 2006).

Table 1. Trends in supply and demand for ecosystem services. Services in italics show mixed trends in demand, and those in bold show declines in demand (results from MA 2005).

Trend	Provisioning ecosystem services	Regulating ecosystem services	Cultural ecosystem services
Declining supply	*Fuel wood*, genetic resources, biochemical, freshwater, **capture fisheries, wild foods**	Local climate regulation, erosion control, water quality regulation, pest control, pollination, natural hazard regulation	Spiritual and religious values, aesthetic values
Increasing supply	Crops, livestock, aquaculture	Global climate regulation	
Mixed trends in supply	Timber, *cotton*	Water flow regulation, disease control	Recreation and ecotourism

Table 2. Alternative explanations of the environmentalist's paradox.

Hypothesis	Origin of hypothesis	Research assumptions
1. Critical dimensions of declining human well-being are not captured adequately	Debate on how to measure human well-being (Alkire 2002)	We are already suffering from losses in ecosystem services, our human well-being data is insufficient to capture this trend
2. Only provisioning services are important for human well-being. Human well-being is not measurably affected by declines in regulating and cultural ecosystem services	The Green Revolution demonstrated that human well-being dramatically increases with access to more food, which is far more important to well-being than other ecosystem services (e.g., Evenson and Gollin 2003)	Humans will be able to produce sufficient quantities of food; and benefits from food production will not exceed costs of ecosystem degradation
3.Technology and innovation have decoupled human well-being from ecosystem condition	Environmental problems stimulate technological innovations that allow environmental problems to be overcome (e.g., Boserup 1976)	Human ability to solve problems is increasing faster than the speed at which new problems are produced
4. There is a time lag after ecosystem service degradation before human well-being is affected	"Limits to growth" highlighted the idea that a society could develop to such an extent that it degrades the resources that sustain it (Meadows et al. 1972)	There are undeniable limits to the expansion of human activities and inherent uncertainty involved in our understanding of ecosystem behavior

The four hypotheses are:

1. Critical dimensions of human well-being have not been captured adequately, and human well-being is actually declining. Measures of well-being that suggest it has increased are wrong or incomplete.
2. Provisioning ecosystem services, such as food production, are most significant for human well-being; therefore, if food production per capita increases, human well-being will also increase, regardless of declines in other services.
3. Technology and social innovation have decoupled human well-being from the state of ecosystems to the extent that human well-being is now less dependent on ecosystem services.
4. There is a time lag after ecosystem service degradation before human well-being is negatively affected. Loss of human well-being caused by current declines in services has therefore not yet occurred to a measurable extent.

The hypotheses differ in their approaches to analyzing the interplay between ecosystem services and human well-being. The first hypothesis focuses on the measurement of human well-being, the second and third explain the paradox using past trends, and the fourth looks to the future to resolve the apparent paradox. Importantly, each of these hypotheses suggests different policy and management responses to the decline in ecosystem services. Consequently, the extent to which any of these hypotheses is supported will have ramifications for the future well-being of humanity as well as implications for research and management priorities. For example, if well-being is already declining, it will probably continue to decline unless our civilization transforms itself. Alternatively, if food is the chief ecosystem service on which humans rely, then we must ensure that food production is more sustainable and robust to future global change. We articulate and evaluate each of the hypotheses below.

Hypothesis 1: Critical dimensions of human well-being are not captured adequately

This hypothesis suggests that the HDI, the most widely used indicator of human well-being, does not adequately represent human well-being, and that alternative measures or different methods of data interpretation would show that well-being is in fact decreasing at global scales, along with ecosystem services. We test this hypothesis to determine whether there are alternative indicators that show a decrease in global human well-being, or whether data aggregation is masking important downward trends that would be apparent at smaller scales.

We are measuring the wrong variables. We reviewed literature and data on different measures of human well-being to determine whether there was evidence of a declining trend. We reviewed literature that addressed the different quantified aspects of well-being defined in the MA (Alkire 2002). To avoid circular reasoning, we did not include human well-being indices that measure natural capital in our analyses. We also did not address aspects of well-being that have not been measured globally, such as psychological health, social solidarity, or cultural change.

The indicators that are components of the composite HDI, specifically, GDP per capita, childhood survival, and education, are all improving at the global scale (WRI 2009). Although the HDI captures only some dimensions of human well-being, it is strongly correlated with other dimensions. A review by McGillivray (2005) found that health-adjusted life expectancy, adult and youth literacy, gender equality, and other measures are strongly correlated with the HDI. The most widely used data set for comparisons across nations of more abstract well-being indicators (such as happiness) is the World Values Survey (WVS; EWVS 2006), which shows a positive relationship between happiness and the HDI (Leigh and Wolfers 2006). Additionally, studies of social capital, or the value placed on social ties and networks, show a strong correlation with the subjective perceptions of happiness from the WVS (Bjornskov 2003), and thus with the HDI.

Some measures of human well-being show more ambiguous trends. Personal security is one dimension of human well-being that does not show clear trends, and by some measures is worsening at the global scale. For example, the total number of people displaced by warfare has increased since the 1940s

(Mack 2005). Crime, as measured at the global level, including rates of homicide and rape, has more than doubled since the 1970s; however, because these data track reports of incidents rather than the underlying crimes themselves, they may not accurately reflect actual crime (Mack 2005).

Human exposure to natural disasters, which is often directly linked to the degradation of regulating ecosystem services, has increased globally since the 1950s (EM-DAT 2007, IPCC 2007). However, the ability of societies to cope with natural disasters has also increased as a result of technological advances, greater wealth, and better preparedness (IPCC 2007). As a result, while the number of people affected by disasters has increased and the economic impacts of disasters have tripled since 1975, natural disaster–related mortality has decreased globally (IPCC 2007). Because measures of well-being such as life-expectancy and income already indirectly incorporate the costs of disasters, it is difficult to argue that greater disaster damage outweighs steady rises in other indicators of well-being. Consequently, despite weak evidence of declines in some aspects of well-being, existing global data sets strongly support the MA finding that human well-being is increasing.

Data aggregation masks declines in human well-being. Measuring average well-being across entire populations may cause us to overlook negative trends among segments of populations, or the effects of increasing global inequality. Nonetheless, the absolute number of people living in poverty—across a range of definitions—has consistently declined at the global scale over the past half century, with the percentage of people living in poverty dropping even faster (figure 2a; Sala-i-Martin 2006, Pinkovskiy and Sala-i-Martin 2009). Global inequality trends vary depending upon the definition of inequality used; inequality among countries is decreasing, whereas inequality within countries is increasing, and overall inequality across all people in the world is declining (Pinkovskiy and Sala-i-Martin 2009).

To focus on the nonincome aspects of well-being among the worst off, we examined the well-being of two categories of people that are expected to be particularly sensitive to declines in ecosystem services: rural people and the very poor. Because of the limited availability of subnational data, we took an indirect approach to this analysis and compared human well-being among groups of countries that have either very high or very low numbers of poor or rural people. One important contributor to the well-being of the impoverished is access to improved sanitation; we used this variable to examine changes in well-being between the rich and poor, as well as between rural and urban populations.

Although the HDI is higher in highly urbanized and wealthier countries, this measure is rising across all groups. In terms of access to sanitation, rural and urban areas are both improving, but gains in poor and predominantly rural countries are most pronounced (WRI 2009). In general, although poor and rural populations are worse off in absolute terms, according to many indicators their well-being is improving just as quickly or even faster than the well-being of wealthy and urban populations (figure 2b).

To conclude, the body of evidence does not support the hypothesis that a more comprehensive assessment of human well-being would resolve the environmentalist's paradox by revealing declines in human well-being. Although there may be ways in which human well-being is decreasing, there are no credible indicators of human well-being that show this decline at the global scale. Most well-being indicators are strongly correlated with the HDI and indicate that human well-being is, on average, growing.

Hypothesis 2: Food production is more crucial than other ecosystem services for human well-being

This hypothesis proposes that the benefits associated with greater provisioning services, in particular, food production, outweigh the costs of declines in other services. By improving crop yields in many developing countries, agricultural innovations associated with the Green Revolution have contributed to higher caloric intake and decreased child malnourishment by as much as 14.4% and 7.9%, respectively (Evenson and Gollin 2003). Globally, the production of grains, meat, and fish has more than kept pace with population growth, meeting the basic needs of people in most regions of the world and allowing for increases in health and life expectancy (WRI 2009). Trends in the HDI are clearly correlated with food provisioning services, and especially meat consumption (Smil 2002). Therefore, to test this hypothesis, we focus on whether declining trends in regulating, cultural, and supporting ecosystem services have as important an impact on human well-being as do the gains in food ecosystem services.

We searched for impacts on human well-being related to decreases in nonfood ecosystem services using national-level data in order to reveal human well-being trends at the global scale. At the global scale, forest cover, biodiversity, and fish stocks are decreasing, while water crowding, soil degradation, natural disasters, global temperatures, and carbon dioxide levels are on the rise, and land is becoming increasingly subject to salinization and desertification (MA 2005, Bennett and Balvanera 2007). However, across countries, we found no correlation between the HDI and the available data on nonfood ecosystem services, including forest cover and percentage of land under protected-area status (proxies for many cultural and regulating services), organic pollutants (a proxy for air and water quality), and water-crowding index (a proxy for drinking water availability; Sieswerda et al. 2001, WRI 2009). This was not surprising, as confounding factors make it difficult to separate the effects of ecosystem service trends from other impacts to aggregated human well-being, such as those from governance, health care, and education.

Health is the component of well-being most easily linked to trends in some nonfood ecosystem services, such as clean water provision and disease regulation; however, national- and global-scale data do not reveal easily interpretable relationships between ecosystem service trends and health (WRI 2009). Global epidemiological studies have argued

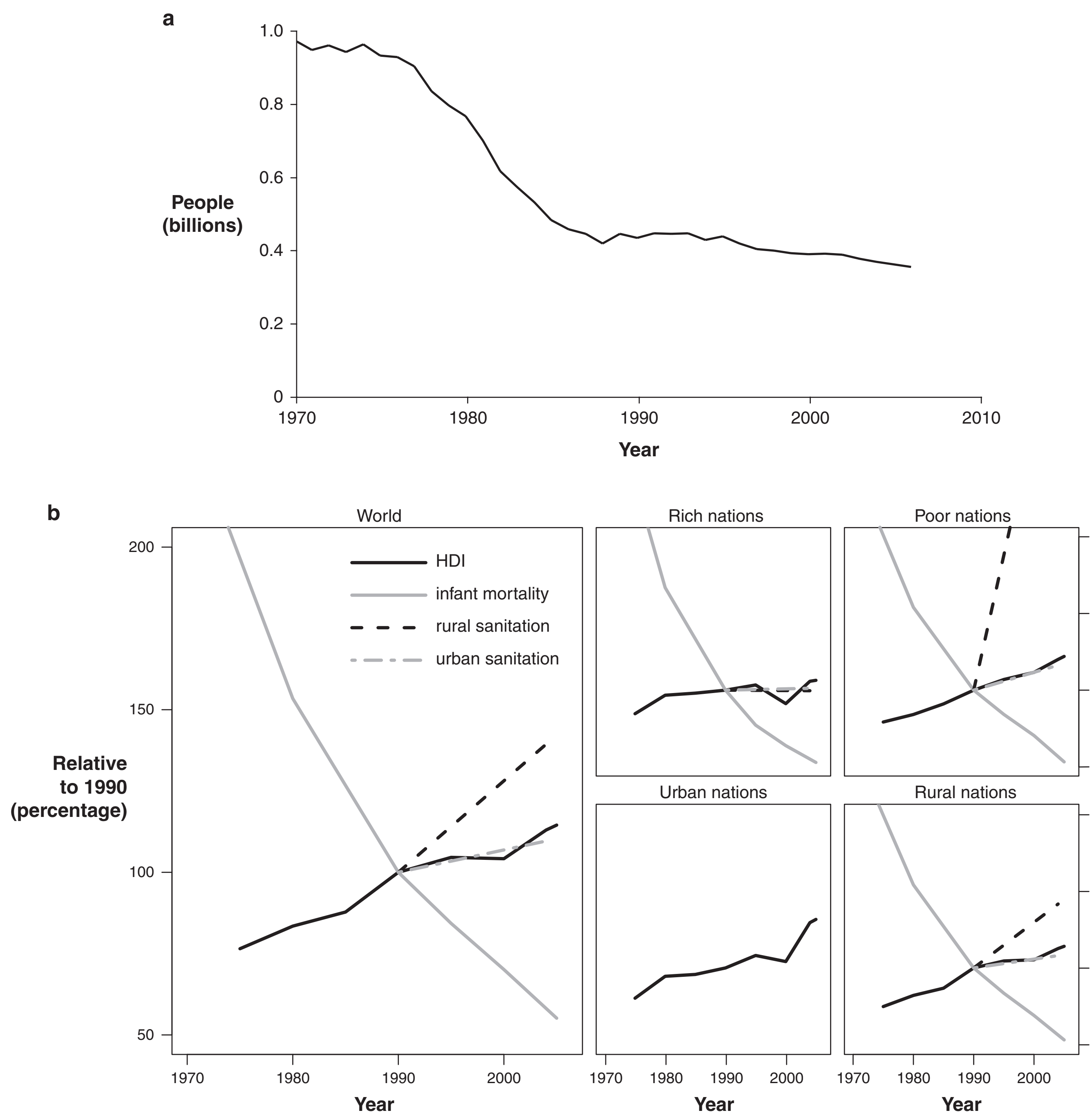

Figure 2. Various aspects of the well-being of poor people have improved. (a) The number of people living in extreme poverty (below $1 per day) has declined over the past 35 years (Pinkovskiy and Sala-i-Martin 2009). (b) Trends in selected indicators of human well-being across different groups of countries. Rich and poor country groups are defined as being in the top and bottom quintiles of gross domestic product per capita (purchasing power parity values). Urban and rural groups are defined using the bottom and top quintiles of the percentage of the population being rural. Human development index (HDI) values are from United Nations Development Programme human development reports (UNDP 2006); all other data are from the World Resources Institute (WRI 2009).

that a significant portion of the global burden of ill health is attributable to degraded land, water, and air; for example, 8% to 10% of malnutrition cases may be attributable to land degradation (Smith et al. 1999). Other studies state that as much as 40% of world deaths are due to environmental degradation, although the term "environmental" is used in the broadest sense to include all forms of pollution and some lifestyle choices (Pimentel et al. 2007). Environmental health scientists suggest that in many parts of the world, the environmental carrying capacity has been exceeded, and people in these areas will suffer from crop shortages caused by erosion and other forms of soil degradation, fish shortages, health impacts from poor sanitation and lack of drinking water, and conflict over resources (McMichael 1997). It is likely that net human well-being could be higher if these issues were better managed; however, at present we do not see a clear effect of these human well-being trends in national or global data sets.

In theory, the cumulative effects of ecosystem service degradation could exert a dampening effect on human well-being at the global scale without reversing positive trends in well-being. Although trends in well-being have risen in conjunction with food production, there may be a threshold at which the mounting costs associated with losses of other services outweigh further gains in well-being from additional food production. For example, in contrast to some multifunctional food production systems, many industrial food production systems in which the HDI continues to rise have become depopulated of human communities, have suffered decreased water quality, have lost many regulating ecosystem services and biodiversity, and are no longer areas of cultural or recreational importance (Brouwer et al. 2008). Net human well-being could theoretically be higher in these areas if food production were achieved without degrading these other services; however, this dampening effect is difficult to demonstrate at large scales. A negative effect of the loss of multiple ecosystem services on net human well-being has been observed at smaller scales (figure 3; Barbier et al. 2008). We tested this relationship using national-level data on the proportion of land a country dedicates to agriculture compared with its HDI, as many ecosystem service declines are the result of trade-offs to increase food production (DeFries et al. 2004). We found no effect on the national HDI from the proportion of land dedicated to agriculture. More complete global scale data sets on various ecosystem services are needed to test this relationship further.

Evidence of the costs to human well-being associated with nonfood ecosystem service loss can be found at local and regional scales. Examples of such costs include sedimentation and erosion impacts on hydroelectric operations and drinking water; loss of wild medicines and the effects of infectious diseases on human health; social or health effects of reduced contact with nature (e.g., Kaplan and Kaplan 1989); and costs associated with losses of wetlands and coral reefs that provide flood protection and support fisheries, as well prevent coastal erosion (Pauly et al. 2003, FAO 2008). Hurricane Katrina's disastrous and costly impacts on New Orleans were in part caused by the losses of regulating services in the surrounding wetlands (Costanza et al. 2006). Of particular concern is evidence that the degradation of regulating and supporting services has undermined the production of food services in the past—for example, by contributing to desertification during the Dust Bowl years in the United States, and in the Sahel during the 1980s and 1990s (MA 2005).

In conclusion, available evidence suggests that the benefits of food production currently outweigh the costs of declines in other ecosystem services at the global scale, and that this is a strong contributing factor to the environmentalist's paradox. However, we also found considerable evidence at smaller scales that the loss of supporting and regulating services can have significant direct effects on human well-being (e.g., through increased floods), as well as indirect effects through impacts to food production.

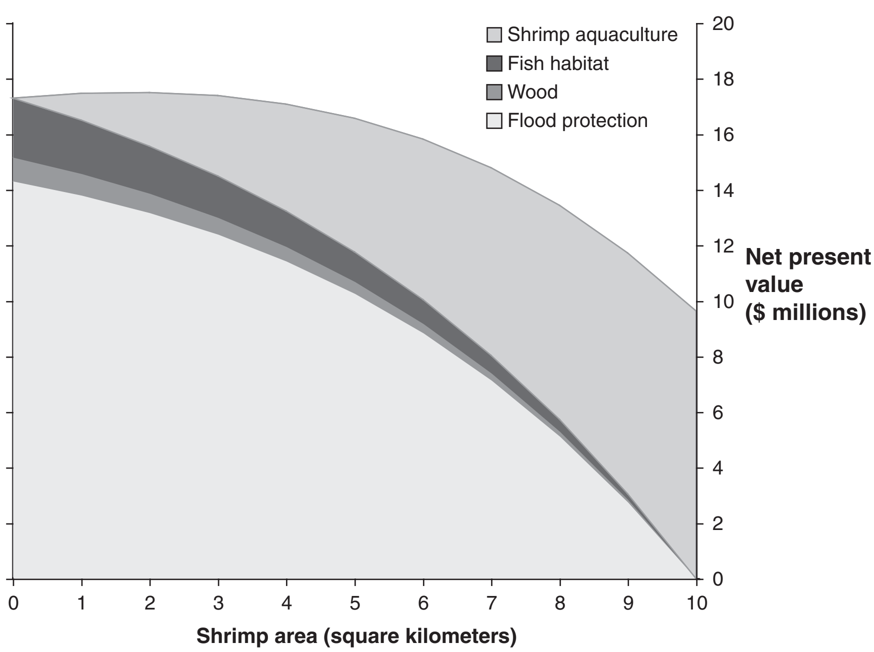

Figure 3. The conversion of mangrove forests to shrimp matriculture in Thailand provides an example a trade-off between agricultural ecosystem services and other ecosystem services. Analysis by Barbier and colleagues (2008) shows that when a small amount of coastal mangrove is converted to shrimp farming, the net benefit from ecosystem services increases, but then decreases as the amount of conversion increases.

Hypothesis 3: Technology and social innovation have decoupled human well-being from ecosystem degradation

This hypothesis suggests that ecosystem degradation does not affect human well-being because human ingenuity has decoupled us from our dependence on ecosystems. We examine evidence that greater efficiency of use and substitution of ecosystem services has significantly lowered human reliance on their provisions.

An increasingly efficient use of ecosystem services could reduce the total demand for services. We found abundant examples of ecosystem services being more efficiently used through the development of new forms of social organization, such as trade, as well as through methods of manipulating and using ecosystem products. For example, improvements in energy-use efficiency, transportation, logistics, and preservation have enhanced the benefits that people can gain from ecosystem processes (Nelson et al. 2006). Perhaps one of the clearest examples of this progress is humanity's rising ability to grow more food on smaller amounts of land (figure 4a). In some parts of the world, each unit of food is now grown with less application of fertilizer (Cassman et al. 2003). The aggregate efficiency of the global economy has increased, as well. The amount of carbon fixation required for each dollar of global economic production (gross world product) has declined by 1.3% per year since 1970 (figure 4b; Canadell et al. 2007). Growing efficiency in the use of ecosystem services would allow humanity to survive on a decreasing stock of ecosystem services, as long as efficiency gains exceed declines in services.

Despite these large gains in efficiency, humans' overall use of ecosystem services has not declined, and demand is in fact growing for 80% of the services investigated by the MA (MA 2005). Growth in demand has more than kept pace with improvements in efficiency, as is shown for fossil fuels and crop production in figure 4. For example, during the same period when the carbon efficiency of the global economy was increasing at 1.3% per year, the total size of the economy was growing at about 3.2% per year, thus increasing the total demand for carbon sequestration services (Canadell et al. 2007). Greater efficiency has therefore not yet reduced societies' use of ecosystem services.

Fossil fuels, technology, and innovation have allowed people to substitute reliance on engineered services for ecosystem services. Fossil fuels have greatly enhanced human well-being with minimal additional use of ecosystem services by allowing people to make use of energy accumulated over the history of the biosphere. Furthermore, medicine, improved sanitation, and better water sources have compensated for widespread deterioration in water quality and have greatly reduced child mortality (Cohen 1995). The construction and operation of infrastructure to replace degraded ecosystem services—for example, irrigation and flood control, the breeding of novel crop varieties, and the use of fossil fuels to produce artificial fertilizers and pesticides—have increased the benefits people are able to extract from agriculture (Evenson and Gollin 2003). Smil (2002) estimated that about 40% of all protein in human diets depends on nitrogen fertilizer produced from fossil fuel. To date, productivity gains from artificial fertilization have exceeded losses resulting from declines in natural soil fertility and water infiltration in soil, and slowed the expansion of agriculture into other ecosystems (Tilman et al. 2002).

There are, however, considerable limitations to technology's ability to replace ecosystem services. First of all, most substitutes do not replace ecosystem services but extend their benefits or functionality; this is the case in most water filtration plants, for example (Brauman et al. 2007).

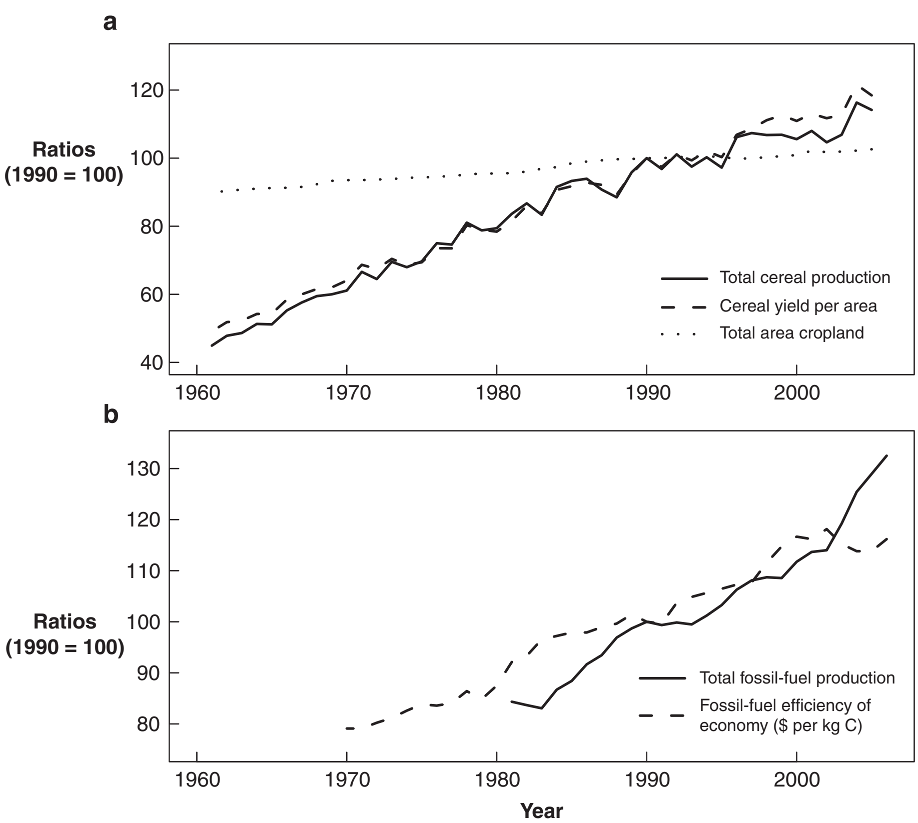

Figure 4. (a) Trends in the production and consumption of cereals, and (b) trends in the production and consumption of fossil fuels. In both cases, the solid line represents total global consumption, whereas the dashed line represents the average intensity of that use. Intensity is defined as the amount of input required for a given output, and as such is the opposite of efficiency. Cereal use intensity (a) is represented as the area of cropland (dotted line) needed to produce a ton of cereal, whereas intensity in fossil fuels (b) is represented as the mass of carbon required for $1 of economic production. In both cases, intensity is decreasing (i.e., efficiency is increasing) while total consumption increases. Data on intensity of fossil-fuel use from Canadell and colleagues (2007); total fossil fuel production and all agricultural data are from WRI (2009). C, carbon; kg, kilogram.

Additionally, Ehrlich and Goulder (2007) suggested that substitution is not possible once the stock of the original resource falls below some critical value. Even before such thresholds are reached, substituting artificial services for ecosystem services can be expensive, both in terms of the substitutes' development and maintenance costs, and of the forgone benefits of alternative uses of ecosystems (MA 2005). Ecosystems simultaneously produce "bundles" of multiple ecosystem services (Raudsepp-Hearne et al. 2010), whereas technological substitution often replaces only one service. For example, in a review of ecosystem services provided by a seascape of mangroves, coral reefs, and seagrass systems, only 5 of the 19 identified services were substituted through single-service approaches such as aquaculture or a water treatment plant (Moberg and Ronnback 2003). Shrimp aquaculture is supported by enormous swaths of land used to supply a single ecosystem service instead of the dozens of services provided by the coastal ecosystems they replace, which are worth far more when valued explicitly (Barbier et al. 2008).

In summary, the increasing efficiency with which we are able to benefit from provision of ecosystem services suggests that there is a potential for reducing our vulnerability to future ecosystem service losses, but this has yet to occur and may depend on our ability to curb the rising global consumption of resources. So far, evidence suggests that technological innovation can only partially and locally decouple human well-being from the use of ecosystem services, and that we have used technology mainly to extend our dominion over Earth's ecosystems. If social systems have not been decoupled from ecosystems, then the steadily increasing demand for ecosystem services would be expected to have impacts on human well-being.

Hypothesis 4: There is a time lag between ecosystem service degradation and impacts to human well-being

This hypothesis argues that we have yet to see global consequences to human well-being as a result of ecosystem service decline because of a time lag between the accumulating effects of human transformations of ecosystems and the impact of these changes on human well-being. Here we examine evidence regarding whether we will eventually reach limits to resource use, and we explore the likelihood of important declines in human well-being in the future resulting from the loss of ecosystem services.

Limits to resource use and interference with ecological processes. Evidence suggests that we are approaching the limits of resource use at the global scale. Recent studies have shown that humans have a larger footprint than the ecological carrying capacity of the world (Wackernagel et al. 2002). This "global overshoot" is only temporarily possible, and depends on the presence of natural capital stocks to be depleted (Wackernagel et al. 2002). However, the capacity of ecosystems to produce many ecosystem services is now low, according to the MA. Estimates of human appropriation of net primary productivity (NPP) suggest that it cannot expand much more, as humans already consume a large proportion of Earth's NPP (Vitousek et al. 1997). Marine fisheries around the world are substantially depleted (Worm et al. 2006); humans already appropriate 50% of global freshwater runoff, and use is increasing (Vitousek et al. 1997). The availability of new sources of high-quality energy is limited (Day et al. 2009).

Human action is also pushing ecosystems beyond their limits, toward irreversible ecological changes. Thresholds are common in complex systems and have been observed in climate-change impacts, soil salinization, desertification, invasive species, fire regimes, and other processes in many parts of the world (e.g., Chapin et al. 2000, Scheffer et al. 2001, Walker and Meyers 2004). For example, human-induced climate change is leading to the melting of polar ice caps, a process that may be approaching a tipping point (Lenton et al. 2008). Agriculture's modifications of hydrological processes are driving local and regional ecosystems beyond thresholds (Gordon et al. 2008). Eutrophication and desertification provide examples from across the globe of threshold-related regime shifts with serious consequences for human well-being (MA 2005). For example, the number of areas experiencing coastal eutrophication has continually increased since the 1950s, negatively affecting fisheries and tourism (Diaz and Rosenberg 2008).

The possibility of limits. As we approach the limits to resource use and alterations to biogeochemical cycles, humanity risks the predictable outcome of running out of resources, or the less predictable outcome of sudden declines in the production of threshold-related ecosystem services. Accumulating evidence at the subglobal scale of the links among ecosystem service degradation, the simplification of ecosystems, and nonlinear system behavior indicates greater risk of resource collapse and associated impacts to human well-being (Folke et al. 2004). For example, climate change, the simplification of food webs, and ocean acidification are projected to synergistically cause the collapse of most of the world's coral reefs (Hoegh-Guldberg et al. 2007). Tens of millions of people are thought to depend directly on coral reefs for their livelihoods, protection, or sustenance. Further examples include collapses already occurring in regional fisheries around the world, which could cascade to the global level (see figure 5a; Mullon et al. 2005), and desertification in many arid regions caused by climate change and the overuse of soils (MA 2005).

There is growing evidence of approaching resource collapses in certain regions of the world, but less is known about how system- or service-specific collapses may interact with one other and result in major impacts on global human well-being. Local or regional collapses may lead to cascading problems associated with forced human migration and resource competition, which could have global-scale effects on human well-being (Warner et al. 2008). Alternatively, market forces and trade rules could cause rapid destabilization in resource markets, leading to outcomes such as the multiple food, oil, and financial crises of 2008, which took the world by surprise (figure 5b; Headey and Fan 2009). The global financial crisis of 2008 also demonstrates the connectivity of the global economy, and the capacity of globalized systems to undergo abrupt and surprising declines. Whether human well-being will suffer at the global scale will depend on how humans adapt to ecosystem degradation and its associated collapses over the next few decades.

Human adaptation to ecological degradation. In the face of strong evidence of increasing ecosystem brittleness, resource depletion, and continuing changes to global biogeochemical cycles, there is mixed evidence regarding whether humans will be more or less able to adapt to current and future ecosystem degradation than they have been in the past. Humans are more educated, wealthier, and better technologically equipped than ever before, all of which favor greater adaptation to global change (Homer-Dixon 2000). Highly adaptable human societies have at times successfully staved off the effects of environmental degradation by importing ecosystem services from other regions, enhancing the supply of ecosystem services in some areas, exporting negative impacts to other locations, and making more efficient use of ecosystem services.

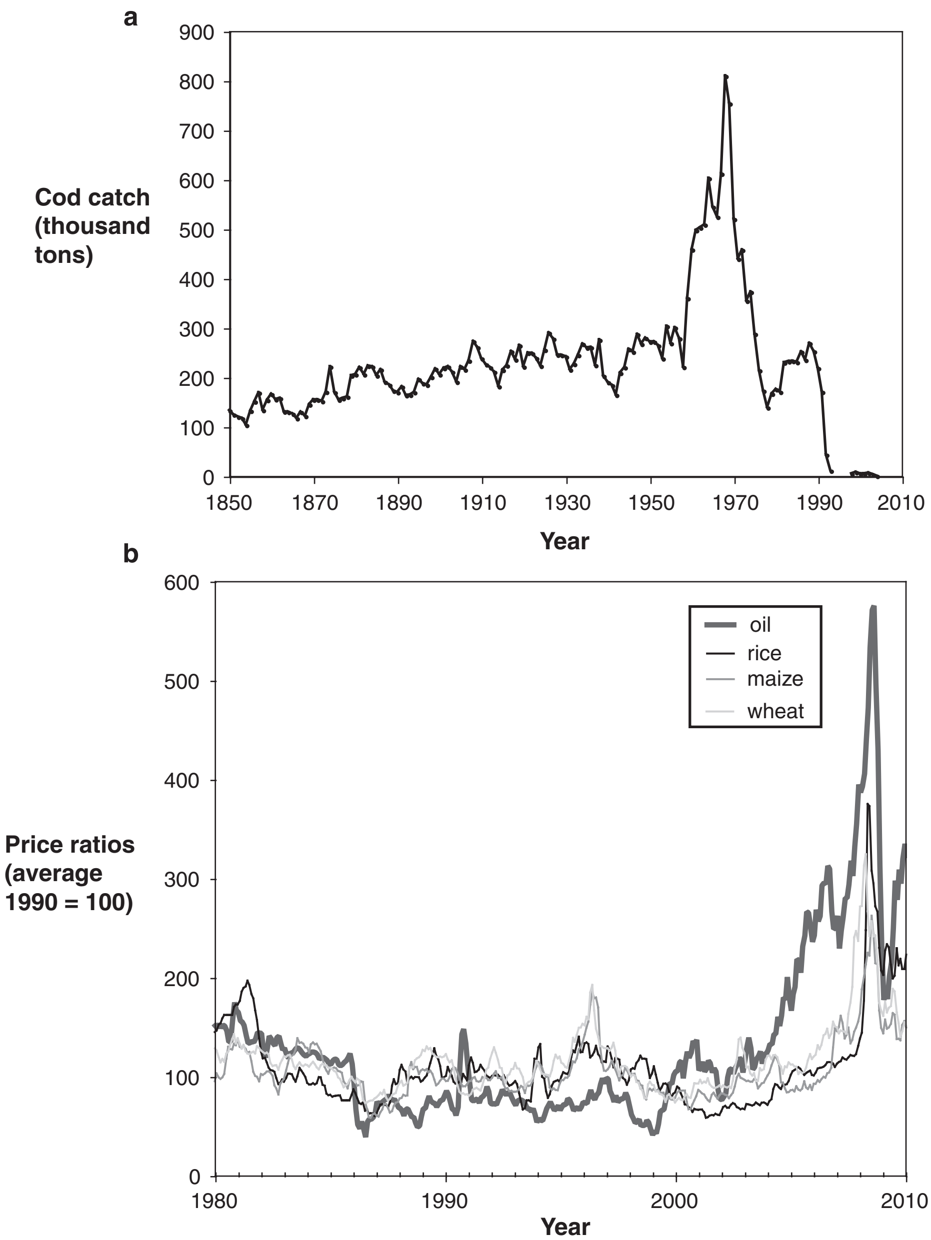

Figure 5. (a) After centuries of overfishing, the Canadian cod fishery abruptly collapsed in the early 1990s. Despite almost 20 years of fisheries closure, cod populations have not recovered (MA 2005). (b) Oil and food prices spiked after decades of relative stability. Some types of food, such as rice, increased much more than food prices in general (data from IMF 2009).

However, evidence suggests that future adaptation will be different and probably more difficult, as resources near depletion at the global scale. Previously available options for migration and translocations of resource use are increasingly constrained by the scope of human use of the biosphere (Vitousek et al. 1997). Humans have been able to adjust to increased pollution, decreases in soil fertility, and other ecosystem degradation at smaller scales; however, there is evidence of a widening gap between the intensity and complexity of global change and humans' ability to adapt rapidly and effectively on a large scale (Homer-Dixon 2000). For example, there has been little effective response from the global community on climate change, indicating social inertia in the face of even a well-recognized challenge (Adger 2000).

The existence of thresholds, nonlinearities, and inertia in ecological systems complicates human adaptation to ecosystem service declines. These features make it more difficult to predict and manage future supplies of ecosystem services. For example, climate models show that inertia in human response to changes in the global climate system could result in warming that will occur for centuries to come—even if greenhouse gas emissions are drastically reduced—causing greater impacts to human well-being than are currently being experienced (Solomon et al. 2009). Steady declines in regulating ecosystem services, which underlie the sustainable supply of many other types of ecosystem services, often go unnoticed until their associated thresholds have been surpassed (Carpenter et al. 2009). Societies have generally failed to anticipate or mitigate the effects of surprising changes in ecosystems, making the rising likelihood that these types of changes may occur even more daunting.

In summary, anthropogenically driven ecological change has substantial and novel impacts on the biosphere. These changes present new challenges to humanity. The existence of a time lag between the destruction of natural capital and the decline in ecosystem service production provides an explanation of the environmentalist's paradox, but uncertainty about the duration, strength, and generality of this lag prevents us from providing strong support for this hypothesis. However, evidence of past collapses and of declines in natural capital does mean that this hypothesis cannot be rejected.

Integrating human well-being and ecosystem services

The environmentalist's paradox is not fully explained by any of the four hypotheses we examined. Our evidence indicates that we can largely reject the hypothesis that human well-being is decreasing; however, some aspects of each of the other three hypotheses are supported, whereas other aspects are invalidated (table 3). For hypothesis 2, it is clear that agriculture provides benefits to humanity, but locally those benefits can be outweighed by the loss of other services. The efficiency with which people have been able to extract benefits from nature has increased, supporting hypothesis 3, but technological innovation has not decoupled society from the biosphere. And while there are many important time lags in Earth's systems, which supports hypothesis 4, the consequences of those lags for human well-being are unclear.

Each of these hypotheses derives from different academic traditions, including agricultural science, economics, and systems science, but the complexity of interactions among the hypotheses and the inherent contradictions within each hypothesis suggest that none of these disciplines alone is sufficient to understand humanity's relationship with the biosphere. The food crisis of 2007–2008 illustrates how food, innovation, and time lags are intertwined with the ways people benefit from ecosystem services. The recent abrupt spike in food prices was driven by rapid jumps in the price of wheat, corn, and rice to more than three times above historic levels (figure 5b). A combination of high oil prices, increased costs of agricultural inputs, and the promotion of biofuels by wealthy countries led to the spike in food prices (Headey and Fan 2009). As predicted by hypothesis 2, the rise in food prices had a negative impact on human well-being. Poor people spend a large portion of their household income on food; consequently, higher food prices can push them into worse poverty, malnutrition, or even starvation, resulting in permanent negative effects on human well-being. However, the recent crisis also illustrates how technological and social innovations, such as biofuels and global trade, can result in decreased human well-being, counter to what is expected from hypothesis 3, and how connections between places and activities can lead to abrupt changes in unexpected places. As international trade transmits the consequences of biofuel production around the world, it also allows regions with insufficient agricultural production to enhance human well-being through food importation. However, by tightening connections between local and global markets, the decline of local food-producing ecosystems makes people more susceptible to rises in global food prices. Finally, the abrupt behavior of the international food markets demonstrates that an underlying assumption of hypotheses 2 and 3—that the past provides a good guide to the future—is not always valid, and that understanding the dynamic interactions between people and ecosystems requires reasoning based on the ideas underlying hypothesis 4, which acknowledge systemic interaction, uncertainty, and abrupt change.

As the previous example illustrates, in order to use human expertise and innovation to nurture a biosphere that enhances human well-being, we must expand our understanding of the complex cross-scale interactions between ecosystem services, human activities, and human well-being. On the basis of our analysis of the

Table 3. Summary of evaluation of hypotheses.

Hypothesis	Evaluation	Supporting evidence
1. Critical dimensions of declining human well-being are not captured adequately	Rejected	Empirical, strong
2. Only provisioning services are important for human well-being	Supported	Empirical, strong for importance of food Lack of data to address importance of other ecosystem services
3. Technology and social innovation have decoupled human well-being from ecosystem conditions	Decoupling of society and ecosystem condition theory rejected Support for enhanced efficiency of ecosystem service use	Empirical, strong against decoupling of society and ecosystems, and for long-term increases in efficiency
4. There is a time lag after ecosystem service degradation before human well-being is affected	Mixed evidence	Weak empirical support mainly on the basis of regional case studies with limited general power Strong support from theory and modeling Difficult to identify counterevidence, therefore strong warning signs

environmentalist's paradox, we suggest that if we are to unravel this problem and better understand how human well-being relies on ecosystems, we need research that integrates human well-being, agriculture, technology, and time lags with ecosystem service research. We propose four research themes: how ecosystem services produce multiple aspects of human well-being, ecosystem service synergies and trade-offs, technology for enhancing ecosystem services, and forecasting the provision of and demand for ecosystem services.

How provision of ecosystem services enhances multiple aspects of human well-being. Research on human well-being has greatly expanded over the past few decades; however, there is little qualitative or quantitative research on how different aspects of human well-being are influenced by changes in ecosystem services. Research on ecosystem services and human well-being has focused on provisioning services and material human needs, and to a lesser extent on the links between ecosystem services and human health and security (MA 2005). There is a need for more research that conceptualizes and measures how different types of ecosystem services contribute to all aspects of well-being. In particular, scientists need to better understand the contribution of regulating and cultural services.

We focus on cultural and regulating services because they are likely to be important for human health and security, and because they are currently understudied. Regulating ecosystem services appear to play a critical role in sustaining local livelihoods and providing capacity for recovery and regeneration following natural disasters or social shocks (Bennett et al. 2009). Although humanity's capacity to cope with disasters has increased (see hypothesis 1), this capacity is not equally distributed across the globe, and poor people are often the most exposed to natural disasters. Consequently, maintaining or increasing the well-being of vulnerable populations may be achieved through the enhancement of regulating ecosystem services in critical areas. In addition to being socially and culturally important, cultural services are often economically valuable and can provide substantial contributions to material well-being, for example, through tourism. Although there is research on the economic value of cultural ecosystem services linked to tourism, there is less understanding of their broader impacts on human health and well-being. For example, an emerging body of literature suggests that environmental change can disrupt the people's sense of identity and place, which may underlie multiple aspects of human well-being (Albrecht et al. 2007). The challenge of understanding the role of regulating and cultural ecosystem services in human lives requires that scientists more fully integrate the roles of human infrastructure, culture, and values into ecosystem service research. Such an integration is necessary if we are to avoid ecosystem services being defined and studied solely in relation to their ability to provide humanity's material needs (Norgaard 2010).

Ecosystem service synergies and trade-offs. Although the ecosystem services concept is widely applied, the ecology of ecosystem services remains poorly understood (Kremen 2005). Fundamental issues must still be addressed, including how multiple ecosystem services are coproduced by ecosystems, and the relative roles of biodiversity, landscape pattern, the human-built environment, and material and energy flows in producing different services (Bennett et al. 2009).

A particular challenge is to understand the factors that influence the temporal dynamics of ecosystem services, as well as the temporal trade-offs and synergies among multiple services. Understanding the temporal dynamics of ecosystem services requires a deeper appreciation of how alterations to ecosystem structure, such as nutrient accumulation and changes in biodiversity, influence the supply of ecosystem services over time. Nonlinear change associated with the provision of ecosystem services has been observed in several ecological systems (figure 5a), and understanding thresholds associated with service provision is crucial in ecosystems subject to rapid, human-induced change. Particularly important questions include how drivers of ecosystem change, such as fertilization, alter multiple ecosystem services, and how regulating ecosystem services maintain the reliable production of other ecosystem services (Bennett et al. 2009).

Human integration with Earth's biosphere (Ellis and Ramankutty 2008) and humanity's reliance on food production require that we develop ecosystem research and management practices that enable people to effectively manage ecosystems for the production of multiple ecosystem services at multiple scales. Identifying ways to increase the production of multiple ecosystem services that are beneficial to food production and human well-being in agricultural areas (Raudsepp-Hearne et al. 2010), while avoiding abrupt ecological changes in these areas (Gordon et al. 2008), are important areas of research.

Technology for enhancing ecosystem services. There is great potential for using technology to proactively enhance the generation of ecosystem services rather than using it to replace lost services. Much environmental research assumes that human activities have a negative impact on ecosystems. However, from the perspective of human well-being, human engineering of the environment can produce beneficial outcomes. For example, the transformation of natural systems to agriculture has provided major benefits to humanity. Other examples include the selective clearing of trees to provide views and other aesthetic benefits, and the construction of dams to provide reliable water sources. Rather than focusing only on the reduction of negative human impacts on ecosystems, we need to foster positive impacts as we reduce the negative ones. For example, we might use technology and innovation to enhance multiple ecosystem services in areas around dams, instead of focusing only on water for human consumption. This will require research that defines how people can build social-ecological systems in which feedbacks between society and ecosystems are recognized and explicitly managed.

Agroecosystems and urban ecosystems are two areas where human influence is intensive, and therefore are good areas to develop technologies to enhance multiple ecosystem services.

Large-scale and regional studies have demonstrated strong trade-offs between agricultural production and regulating and cultural services (Raudsepp-Hearne et al. 2010); however, research has also demonstrated that food, fiber, and fuel can all be produced in ways that have a greater or lesser impact on other services. Examples range from developing new farming methods to improving ecological infrastructure, such as riparian zones and ecological corridors. Farming methods to reduce trade-offs could include better-fitting management to temporal and spatial variability in ecosystems, for example, by using weather forecasts and knowledge of soil conditions to precisely target and time fertilizer applications to increase crop yields while reducing unwanted runoff (Gordon et al. 2010).

Most people of the world live in urban ecosystems; consequently, these areas produce many of the ecosystem services that people directly experience. However, there is relatively little research on how urban ecosystems can be designed, built, maintained, and adapted to enhance ecosystem services such as water filtration, climate moderation, flood regulation, and a variety of cultural ecosystem services (Elmqvist et al. 2004). Furthermore, cities cast large ecological shadows because they import products and services from distant places. Enhancing the local production of ecosystem services that support human well-being can enhance the quality of life in cities while reducing the environmental demand on distant ecosystems. However, to achieve such a goal requires the integration of ecosystem service concepts within engineering, architecture, and urban planning.

Forecasting ecosystem services. People's beliefs about the future consequences of our actions are at the crux of arguments about whether humanity will adapt to ecological degradation and thrive, as it has done in the past, or whether declines in ecosystem services will ultimately limit human well-being. Our assessment of the four hypotheses is limited by our reliance on past evidence. Consequently, part of resolving the environmentalist's paradox is improving the clarity with which we predict future conditions. Better forecasting of the dynamics of multiple ecosystem services requires understanding the short-term factors that drive variation in the production of ecosystem services, as well as the long-term changes that may erode the underlying capacity of ecosystems to generate services, such as the loss biodiversity. The roles of technology and trade, trade-offs associated with food production, and time lags need to be considered together to better understand how ecosystem services and human well-being will fare in the future.

Ecosystem services are defined both by human demand for particular services and the ability of functioning ecosystems to supply them. Consequently, understanding the dynamics of ecosystem services requires an integrated understanding of how changes in human desires and activities combine with ecological dynamics to produce change. Building this understanding will involve the development of a science of ecosystem services that moves beyond valuation to (a) quantitatively understand how multiple ecosystems services affect human well-being; (b) understand how human demand, desires, and activities regulate the consumption and production of ecosystem services; and (c) predict how novel ecosystems that are likely to exist or be created in the future—consisting of new combinations of environmental conditions, species, and disturbance regimes (Hobbs et al. 2009)—will produce ecosystem services. Furthermore, statistical reasoning and modeling of ecosystem behavior must accommodate the existence of nonlinear change and cross-scale interactions. These are large challenges for ecosystem service science, but moving toward this goal will improve human capacity to produce ecosystem services that enhance human well-being, and resolve the environmentalist's paradox.

Conclusion

There is strong evidence that humanity has an unprecedented effect on the biosphere, and there is evidence that these impacts are reducing human well-being in some places. However, there is only weak evidence that declines in the global biosphere are reducing aggregate human well-being at the global scale. Evidence presented here suggests that the growth of human well-being despite losses of ecosystem services can be partially explained, but not completely resolved, using available data. Trying to untangle why measures of human well-being are on the rise while ecosystem conditions decline is critical to improving ecosystem management. This conclusion highlights an important but often blurred distinction between human impacts on the biosphere and the biosphere's impact on human well-being. These are clearly two different things, and although we have a good understanding of the negative impacts of much of human action on biodiversity, natural capital, and the biosphere, we have only a weak understanding of the consequences of changes in the Earth system for human well-being. We present future avenues of research that may enhance our capacity to live better on a human-dominated planet.

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"Only the surface has been explored—It could still have a green cheese core."