# Chapter 14
# Human Health as an Ecosystem Service: A Conceptual Framework

**Karen Levy, Gretchen Daily, and Samuel S. Myers**

## Introduction

To live in good health and, in many ways, to live at all, people need a wide array of life-support benefits that derive from ecosystems. Collectively these are called *ecosystem services*, a term referring to the conditions and processes through which ecosystems, and the species that make them up, sustain and fulfill human life (Ehrlich and Ehrlich 1981; Daily 1997; Millennium Ecosystem Assessment 2005). These processes underpin the production of goods (such as seafood and timber), life-support functions (water purification and flood control), and life-fulfilling conditions (beauty and inspiration), as well as the preservation of options (such as genetic diversity for future use).

Ecosystems and human health are thus intimately interlinked. The preceding three chapters illustrate how changes in land use and climate can impact health directly, and how numerous indirect impacts on human health are mediated through changes in the composition of species in a given ecosystem. Here, we explore more directly the ways in which the condition of ecosystems and the health of human populations are linked, and we explore prospects for illuminating these linkages to advance scientific understanding and inform management options and decisions. The kinds of questions that stand out include,

1. Are there practical and reliable indicators of ecosystem condition/function that signal levels of risk to human health?
2. Can change in certain ecosystem attributes (size, configuration, and composition) be reliably translated into changes in health risks?

K. Levy (✉)
Department of Environmental Health, Rollins School of Public Health, Emory University, 1518 Clifton Rd NE, Atlanta, GA 30322 USA
e-mail: karen.levy@emory.edu

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The relationships between biophysical attributes of ecosystems and human communities are complex. Destruction of ecosystems can improve aspects of community health. For example, draining swamps can reduce habitat for the mosquito vector that transmits the parasite that causes malaria, as discussed by Myers, this volume. At the same time, ecosystems provide many services that sustain human health, for which substitutes are not available at the required scale, such as purification and regulation of drinking water flow.

To date, there is little rigorous research establishing the links between ecosystem conditions and human health. In order to understand the complexities of these relationships, there is a need to clarify the factors that confound them, and to establish a common lexicon for ecologists and health scientists to discuss them. In this chapter, we describe some of the evidence that exists to indicate important adverse health impacts from deteriorating ecosystem services, and also outline the reasons that epidemiological evidence for these relationships remains difficult to establish. We also discuss how to move forward not only to establish more clear evidence, but also to help set policy agendas for addressing these relationships.

## Background

Ecosystem services are the conditions and processes through which ecosystems, and their biodiversity, sustain and fulfill human life. Ecosystem services are generated by a complex of natural cycles, powered by solar energy. These cycles operate on a wide spectrum of temporal and spatial scales, from protracted and global biogeochemical cycles to comparatively instantaneous life cycles of tiny bacteria (Daily 1997).

Ecosystem services can be classified by four different types (Millennium Ecosystem Assessment 2005):

*Provisioning services* include the products obtained from ecosystems, such as food, freshwater, building materials, fuels, and precursors to pharmaceutical and industrial products;

*Regulating services* are the benefits obtained from regulation of ecosystems, including flood and storm control, climate regulation, water purification, disease regulation, and carbon sequestration;

*Supporting services* are defined as services needed for the production of all other ecosystem services, and include nutrient dispersal and cycling, soil formation, waste decomposition and detoxification, primary production, crop pollination, and seed dispersal; and

*Cultural services* include all non-material benefits obtained from ecosystems, such as cultural heritage, intellectual and spiritual inspiration, recreational experiences, educational opportunities, and aesthetic value.

The ecosystem services framework allows the benefits that human societies obtain from ecosystems to be explicit in policy considerations (Millennium

**Table 14.1** Some relationships between ecosystem conditions or processes and human well-being

| Ecosystem condition or process | Intermediate ecosystem service | Final ecosystem service | Dimension of human well-being |
|---|---|---|---|
| Biodiversity in oceans | | Production of a wide array of seafood | Nutrition |
| Primary production and herbivory | Herbivory | Production of animal biomass | |
| Predation | Control of agricultural pests | Production of plant biomass for use as food, fiber, timber, and fuel | |
| Pollination | Pollination | | |
| Nutrient cycling | Generation and renewal of soil fertility | | Clothing<br>Shelter<br>Energy |
| | Decomposition of waste | Protection from pathogens and toxins | Health |
| | Purification of water | | |
| Photosynthesis | Carbon sequestration | Climate stabilization | Protection from climate variability (storms, floods, droughts, heat waves) |
| Seed dispersal | Replenishment of natural vegetation | Landscape stabilization | |
| | | Seed dispersal | Economic flexibility and security |
| Ecological stability | | Relatively constant production | |
| Generation and maintenance of biodiversity | Preservation of options | Possibility of using a good or service (e.g., a natural medicinal product or crop pollination) in the future | |
| | | Beauty | Aesthetic inspiration |
| | | Complexity | Intellectual stimulation |
| | | | Diverse cultures |
| | | Serenity | Peace of mind |

Ecosystem Assessment 2005). It also provides a way to consider the losses we might be incurring when we lose well-functioning ecosystems.

From the inception of the concept of ecosystem services in the 1970s and 1980s (Mooney and Ehrlich 1997), health has been widely cited as a main service that ecosystems provide. Table 14.1 illustrates one of the many possible perspectives relating the conditions and processes occurring in ecosystems to key elements of human well-being. Although very simple, this table reveals several important observations.

First, relatively few ecosystem conditions and processes confer direct benefits on humanity, such as in the way some ocean biodiversity contributes, via seafood, to human nutrition. Rather, most ecosystem conditions and processes confer numerous indirect benefits, or "intermediate services." The second column in the table presents a variety of such intermediate services, such as pollination, agricultural pest control, and renewal of soil fertility, all of which contribute indirectly to human nutrition and health. One could easily envision additional columns that would illuminate more intermediate services, revealing more details of pollination, predation, and soil processes.

Second, individual ecosystem conditions and processes contribute to more than one final ecosystem service, and ultimately all lead to aspects of human well-being. This observation holds true in virtually any classification, at any level of detail. Thus, nutrient cycling contributes to nutrition, clothing, shelter, energy, and health. Similarly, predation contributes not only to control of agricultural pests, but also to control of reservoirs and vectors of human pathogens, and thereby to health (this link is not shown in the table).

Third, the inverse of the second point is also true, meaning that maintaining any single aspect of well-being, such as food security, requires attention to a great many aspects of the ecosystems supporting it. Protection from climate variability underscores this point, depending on strikingly different ecological conditions and processes. The two shown in Table 14.1 are photosynthesis and seed dispersal.

Fourth, biodiversity is involved in virtually every part of the table. Indeed, if one were to create a relational table such as this at a very fine level of detail, one could list as intermediate services the conditions and processes required to support each individual population, of each species, involved in each final service (Luck et al. 2003, 2009). Thus, ecosystem services contribute to making human life both possible and worth living, in complex and interesting ways. Because of their basis in cycles, operating over such varying scales, the classification of ecosystem services is inherently arbitrary, a function of context and the most useful point of entry into the cycles, and the appropriate level of detail of analysis.

In some situations, the services provided by ecosystems can be replaced by physical infrastructure (such as water treatment facilities). But in many situations, intact ecosystems provide services more effectively or efficiently than engineered alternatives; sometimes they are irreplaceable. For example, animal-pollinated crops provide one-third of the calories in the human diet (Klein et al. 2007) and pollinator-provided calories (in the form of nuts, seeded vegetables, and fruits) are especially rich in nutrients that support human health. Ongoing declines in populations of pollinators may threaten the crops upon which human communities depend to meet their nutritional needs. While bees have been managed for honey production for thousands of years, only in the past century have people managed bees for pollination services – to crops in highly intensified systems from which natural sources of pollinators have been eliminated (B. Brosi, personal communication, 4/5/09). Refer to the chapter on ecosystem services in agricultural landscapes by Smukler et al., this volume, for additional discussions related to these issues.

Natural watersheds provide a filtering mechanism for improving water quality for human consumption. While water treatment plants can replace this service, the quality of source water entering into water treatment plants can affect the quality of water consumed by human communities even in areas with high investment in water purification systems. There is some evidence to suggest that higher turbidity levels of source water are associated with higher rates of hospital visits for gastrointestinal illness (Schwartz et al. 2000; Mann et al. 2007; Tinker et al. in press). In some cases, it can be more cost-effective to maintain watershed functioning than to build a water treatment plant, and there are examples of this from many cities in the United States and other parts of the world (Postel and Thompson 2005). For example, the city of New York recognized this in their decision to restore the Catskill watershed to provide the city with water purification rather than investing in a water filtration plan (Chichilnisky and Heal 1998). Other municipalities are using managed wetlands as tertiary water treatment facilities (Humboldt State University 2009).

Natural barriers, such as vegetated dunes, reefs, mangrove forests, and wetland systems, can aid in controlling natural hazards, and intact ecosystems in some cases eliminate the need for extensive human engineering to control the forces of nature. In the 2004 Southeast Asian tsunami, the coastal areas of Thailand flanked by several hundred meters of mangrove forests withstood the tsunami's impacts far better than did areas where mangroves had been cut down, such as in Sri Lanka. Coral reefs also had a wave-buffering effect. Recognizing this, in the wake of the tsunami, the Thai government is allowing only a few of the impacted and displaced shrimp farmers to return and instead allocating more land for mangrove forests (Englande 2008). In India, mangroves forest cover has been associated with lower cyclone-associated death tolls (Das and Vincent 2009). Similar management issues concern natural wetlands and barrier islands that once protected the Gulf Coast of the United States from storms like Hurricane Katrina (see chapter by Ingram and Khazai, this volume, for further discussion on coastal disasters).

The threat that the depletion of ecosystem services represents to human health has been acknowledged in various global policy arenas. Policy papers produced by major international undertakings like the Millennium Ecosystem Assessment (MA) (Millennium Ecosystem Assessment 2005) and Global Environmental Outlook (GEO4) (United Nations Environment Programme (UNEP) 2007) contain numerous statements that ecosystem service degradation will have significant impact on human health and well-being and threatens to reverse progress on the Millennium Development Goals (MDGs) (United Nations 2009). The MA is the broadest review to date of ecosystem services research, synthesizing information from scientific, governmental, private, and local sources. According to the MA, "The degradation of ecosystem services is harming many of the world's poorest people and is sometimes the principal factor causing poverty." At the same time the authors acknowledge that "the information available to assess the consequences of changes in ecosystem services for human well-being is relatively limited," (Millennium Ecosystem Assessment 2005). The Health Synthesis of the MA, which summarizes the findings of the MA's global and sub-global assessments of how ecosystem changes specifically affect human health and well-being, concludes that, while "ecosystem services are indispensable to the well-being of people everywhere", "limited information [exists] on the details of linkages between human well-being and the provision of ecosystem services, except in the case of food and water," (Corvalán et al. 2005). Thus we know that human communities depend on nature to provide services and that reduced access to these services below some threshold "should" impact health and well-being. But while we may accept the logic that humans depend on their local environments to diversify their food supply, provide safe drinking water and sanitation, or additional sources of income, how much direct evidence is there that ecosystem service degradation is causing poor health outcomes? Or that good health outcomes are attributable, in part, to good supply of ecosystem services?

Efforts to quantify the relationships between ecosystem services and human health on a large scale have tended to underestimate the complexity of these relationships. Two studies have explicitly explored the association between ecological conditions and human health outcomes (Sieswerda et al. 2001; Huynen et al. 2004). Both studies report the results of linear regression analysis on a global scale, using aggregated country-wide datasets from sources including the World Resources Institute (WRI), World Bank, and World Health Organization (WHO). Neither study's conclusions support the hypothesis that loss of ecosystem services leads to a decline in the health and well-being of human communities. Any relationship that they did find disappeared once indicators of socioeconomic status were controlled for in the models. However, several methodological problems limit the conclusions drawn from this work, many of which were acknowledged by the authors.

## Challenges to Linking Ecosystem and Human Health

The design failures of the aforementioned studies illustrate some of the problems that have plagued this field of inquiry. To move toward a better understanding of the role of ecosystems in supporting human health, we highlight some of these methodological issues, in an effort to move beyond them.

### *Scale of Inquiry*

Both Sieswerda et al. (2001) and Huynen et al. (2004) undertook an analysis of the relationship between ecosystem status and human health at the global scale, using countries as the unit of analysis. This scale of analysis misses many of the complexities of the relationship between ecosystem integrity and human health. Many different human and ecological conditions exist within any given country, urban and rural, wealthy and poor. Rural populations rely heavily on local ecosystem services to support their livelihoods (Gadgil 1998). Communities that rely directly on local or regional ecosystem services will experience the impacts of loss of these services that may not be felt country-wide. In addition, many different biophysical realities exist within any given country. Effects will vary depending on ecosystem type, and even within a given ecosystem, relationships between ecosystem services and health may be scale-dependent. For example, hydrological services are largely regional (Brauman et al. 2007). Thus regional level analyses are needed before data can be aggregated on a global scale. Appropriate variables should be used to stratify data analysis, including characterizations of the ecosystem (e.g., arid vs. wet; high vs. low altitude; tropical vs. temperate) and of the population in question (e.g., urban vs. rural).

## *Measures of Ecosystem Services*

Sieswerda et al. were interested in the broad effects of "ecological integrity" on human well-being and health, whereas Huynen et al. had a more specific focus on biodiversity loss and its effects. Indicators of ecosystem function used by the authors included such variables as percentage of threatened species per 10,000 $km^2$, current forest as a percentage of original forest, percentage of land highly disturbed by human activity, percentage of the country's land mass totally or partially protected, percentage of forest remaining since pre-agricultural times, and average annual change in forest cover.

These measures of ecosystem health address land use and species composition broadly, but do not capture ecosystem services, *per se*. Again, the country-wide scale at which these indicators are measured do not capture regional and local effects. Country-wide metrics of forest cover and species counts provide no information about the spatial distribution of these metrics in relation to the location of human populations.

Many habitat types other than forests provide ecosystem services, and ecosystem services are also provided in working landscapes (Daily 1997), and local sociological, economic, and other human factors are also important factors to consider. More appropriate metrics of ecosystem health with respect to the provisioning of ecosystem services might include measures of water quality and quantity, air quality, food resource availability, or abundance of specific disease vectors or hosts.

## *Definitions of "Health"*

The WHO defines human health as "a state of complete physical, mental and social well-being" (World Health Organization (WHO) 2006). Several different proxies can be used as indicators of overall health. Sieswerda et al. (2001) used life expectancy as the outcome of interest, whereas Huynen et al. (2004) used several different indicators of health: life expectancy, disability adjusted life expectancy (DALE), infant mortality rate, and percentage of low birth weight babies.

While these are useful overall measures of health as an integrated measure of well-being, further insights about the relationship between health and ecosystem services will be gained by stratifying the outcome in question. Lumping all diseases into a broad category of "health" can obfuscate our understanding, because changes to ecosystems will have drastically different effects on diseases of different etiologies. For example, insecticide application for mosquito abatement might reduce the incidence of vector-borne diseases while at the same time increasing the incidence of cancer. Draining swamps might reduce exposure to malaria or West Nile virus but reduce water quality and increase exposure to water-related disease.

The WHO has adopted the global burden of disease (GBD) approach to measuring burden of disease using the disability-adjusted life years (DALYs) metric. DALYs are a time-based measure that combines mortality (years of life lost from premature death) and morbidity (years of life lost due to time lived in states of less than full health). This approach allows for a consistent assessment of the burden of disease across diseases, risk factors, and regions (World Health Organization (WHO) 2009).

Several efforts have quantified the global burden of disease attributable to environmental factors, with estimates of 23–33% (World Health Organization 1997; Smith et al. 1999; Prüss-Ustün and Corvalán 2007). However, the definitions of "environment" used in these assessments were not specific to ecosystem-level change.

A systematic inventory of the burden of disease attributable to changes in particular ecosystem services, stratified by regions and ecosystem types, would help elucidate the varied relationships between ecosystem health and human health (Corvalán et al. 2005). To be sure, burden of disease assessment cannot fully account for complex causal pathways, long timescales, and potential irreversibility of alterations to ecosystems (Corvalán et al. 2005). However, this type of analysis would provide more insight into specific relationships in a way that an aggregated analysis cannot.

## *Data Availability*

Both Sieswerda and Huynen relied on large publically available databases for their analyses; both utilized WRI data and in addition Huynen included data from World Bank and WHO sources. Sieswerda rightly points out that the availability of information depends on a country's ability to collect or willingness to provide data, which is not unrelated to health status. The scale of data used must match the question of interest. Analysis of large datasets can provide important insights if appropriate questions are asked. But in many cases, finer grained data will be needed to address the relationship between ecosystem health and human health at an appropriate scale. Where data exist, a series of analyses at smaller scales can be aggregated to provide insight into more generalizable phenomena. Where such data are lacking, research should be designed and carried out to fill in these gaps. We next discuss approaches to collecting such data.

## *Analytical Approach*

Linear regression, as applied by Sieswerda and Huynen, represents a convenient analytic approach to investigating relationships between explanatory variables and outcomes of interest. However, these techniques cannot account for many of the complexities of the relationships between ecosystem condition and human health. The relationship between different types of resource scarcity and negative health outcomes is not likely to be linear. Effects of ecosystem change on community health are not likely to be felt immediately, but rather experienced gradually over

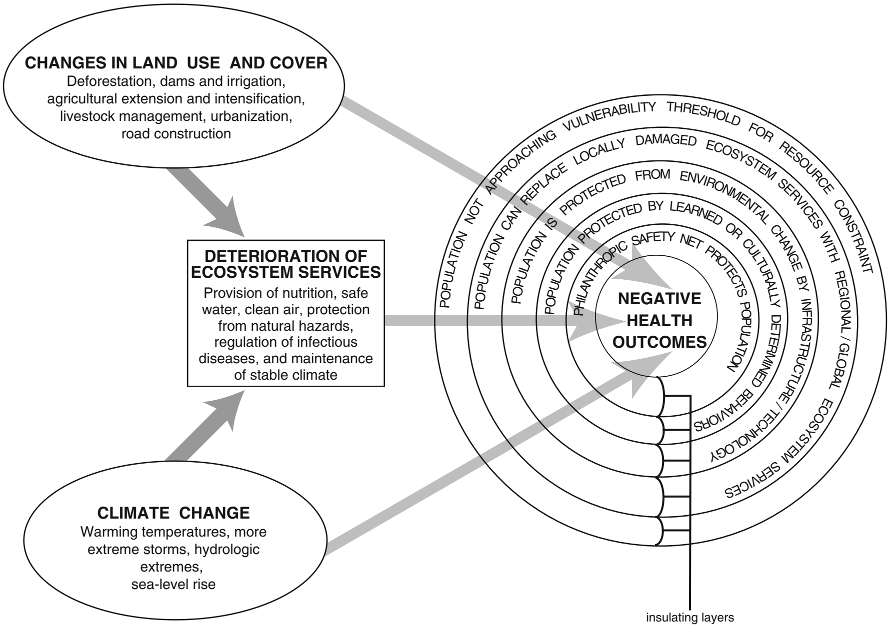


**Fig. 14.1** *A schematic of the complex relationships between altered environmental conditions and human health.* Drivers of global environmental change (e.g., Land use change or climate change) can directly pose health risks, or impair ecosystem services that subsequently influence health. For hazards that affect human health, however, exposures will be modified by multiple layers of social or infrastructure barriers that can buffer or eliminate risk. Together, all components must be considered to achieve realistic assessments of population vulnerability (Reprinted, with permission, from Myers and Patz (2009). ©2009 by Annual Reviews www.annualreviews.org)

time. Huynen notes this effect, explaining that "only when a threshold in the losses of biodiversity is reached, the provision of ecosystem goods and services gets compromised" (Huynen et al. 2004). A strong correlation with health will be reached only when resources are very constrained. Until this "threshold" is reached, depletion of ecosystem services might have little impact on health (Fig. 14.1). Because complex and interdependent causal pathways introduce non-linearity into the relationship, appropriate analytic techniques will be necessary to account for time lags in effect, non-linearity of responses, and threshold effects. We discuss alternative analytical approaches further below.

## *Insulating Factors*

Ultimately, direct relationships between measures of ecosystem health and measures of human health may be difficult or impossible to establish because human populations tend to be insulated from direct impacts of ecosystem service degradation by a

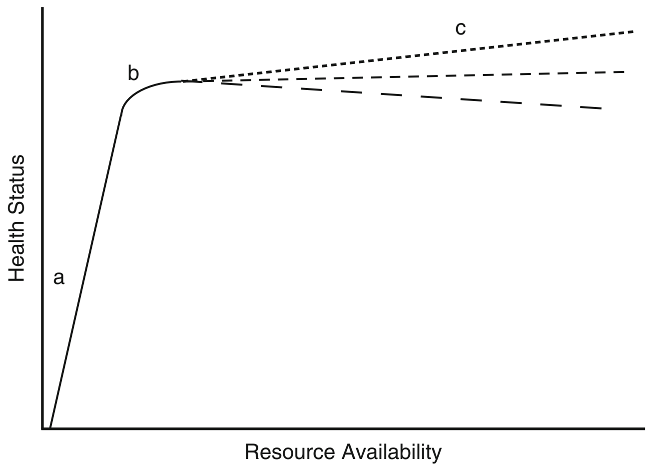


**Fig. 14.2** *A schematic diagram of a proposed relationship between resource scarcity and human health.* When resources are tightly constrained (**a**), increases or reductions in access to them can have significant health consequences. Once access to adequate food, water, fuel building materials, etc. has been achieved (**b**), the relationship between increased access and health gains becomes much less pronounced. Further increases in resource access (**c**) may lead to marginal improvements in health status, but overuse may also lead to reduced health status, for example, excess food consumption and obesity (Reprinted, with permission, from Myers and Patz (2009). ©2009 by Annual Reviews www.annualreviews.org)

variety of mitigating factors (Fig. 14.2). According to the WHO Director General, "Nature's goods and services are the ultimate foundations of life and health, even though in modern societies this fundamental dependency may be indirect, displaced in space and time, and therefore poorly recognized" (Corvalán et al. 2005).

The ability to "trade" ecosystem services through access to local or global markets or philanthropic safety nets, and the ability to mitigate loss of ecosystem services through infrastructure or behavioral practices confound the relationship between ecosystem health and human health. Dasmann contrasts "ecosystem people" and "biosphere people" in terms of the radius over which they have access to resources, and over which they are vulnerable to ecosystem disruption (Dasmann 1988; Gadgil 1998).

"Trading" ecosystem services can occur when locally damaged ecosystem services are replaced by regional or global ecosystem services. In essence, richer countries have been able to buy their way out of the health effects of ecosystem destruction. This is seen with the effect of socioeconomic indicators, such as the Gross Domestic Product, that overwhelm the effect of loss of ecosystem integrity for predicting human health outcomes in both Sieswerda and Huynen's models. Higher income countries are buffered from the effects of loss of ecosystem services with their ability to import these services by accessing goods produced on "ghost acreage" elsewhere (Borgstrom 1965).

Philanthropic efforts represent another sort of "trading" of ecosystem services. For example, the health impacts of a hurricane that hits an area with a heavily degraded ecosystem might be ameliorated by humanitarian relief efforts. Or regions affected by famine or natural hazards may be supported by importing goods and services from outside the affected region. This type of humanitarian assistance may come from national or international organizations.

Technology and infrastructure can also confound the relationship between loss of ecosystem services and subsequent health impacts. Technology such as the introduction of fertilizers for increased food production can insulate populations from altered environmental conditions. Likewise, the development of infrastructure such as water treatment plants to protect against deteriorating water quality or seawalls to protect against storm surges can reduce the impacts of changing ecological systems on human populations. Such measures can replace some of the services provided by ecosystems, or otherwise buffer communities from their loss. Technology interacts with human behavior which represents another type of protective measure. For example, even if microbial water quality has deteriorated, people can treat their water to prevent the ingestion of pathogenic organisms. The use of bednets can also protect against the spread of malaria vectors. To the extent that these behaviors are culturally mediated, however, they may have less ability to adapt to rapidly changing environmental conditions, as these behaviors often evolve over many generations. Technology, infrastructure, and trade are all highly dependent on access to resources, so more impoverished populations will tend to be less buffered to ecosystem degradation than wealthier ones.

Vulnerability, as a concept, includes not only exposure to the health risks associated with changing environmental conditions but also the population-level conditions we have discussed above that make such exposure more or less safe (Turner et al. 2003).

## Relationships Between Specific Ecosystem Services and Health

The ways in which provisioning, regulating, supporting, and cultural ecosystem services support human health and well-being have been reviewed elsewhere (Corvalán et al. 2005). The most direct relationships between ecosystem services and health exist for provisioning of food and safe water and the regulation of infectious disease, climate, and natural hazards. However, even with these apparently direct relationships, there is often a paucity of data showing a direct correlation between deteriorating ecosystem services and adverse health outcomes. Here, we highlight three classes of ecosystem services that have strong and clear relationships with human health. We summarize the salient evidence supporting these relationships, and also describe where more information is needed to determine the strength and direction of the relationship in various different circumstances. In order to illustrate the methodological issues described above, we discuss why it has been difficult to establish the evidence, key confounders, and suggestions for lines of inquiry and approaches to these topics. We focus on the ecosystem services of food production, fresh water supply, and protection from natural hazards. While other ecosystem services, such as regulation of climate and infectious diseases, also have direct relation to human health, they have been covered extensively in the previous three chapters on land use, climate change, and disease ecology.

## *Food Production*

Food production is a key provisioning service as is outlined in the four chapters on ecology and hunger, this volume. Food production as a provisioning service is supported by other services, such as soil formation, biodiversity as a source of new crop varieties, pollination, pest control, climate regulation, water supply, and nitrogen fixation. An adequate supply of food supports human nutritional requirements and overall bodily function, including cognitive development, metabolic and endocrine functioning, reproductive health, immune status, and overall vigor. Food shortages lead to malnutrition, which causes stunting, cognitive impairment, diarrhea, and can ultimately lead to starvation. Worldwide, roughly 16% of the global burden of disease is attributable to childhood malnutrition (Murray and Lopez 1997) and, in 2008, the FAO estimated that 923 million people worldwide are suffering from malnutrition (2008).

During the next 50 years, global demand for food is projected to double (Alexandratos 1999). In certain parts of the world, particularly sub-Saharan Africa and parts of South Asia, rapidly growing populations are already encountering ecological constraints to local food production. Soil degradation and water scarcity have prevented yields from rising over the past 35 years, and, in some areas, they have been falling. Poor access to fertilizers, new crop varieties and irrigation have increased local vulnerabilities to these environmental trends. Future threats to food production include further land degradation, increasing water scarcity, accelerating climate change, and growing demand caused by population growth and increased meat consumption. Loss of wildlife habitat and fisheries depletion also decrease protein intake from hunting and fishing. Given the apparent strength of this relationship between the ecosystem service of food production and nutrition that supports human life, what are the challenges in providing evidence of a link between the depletion of this service and adverse health outcomes?

First, the scale of analysis is critical. Global food production can be a misleading indicator of food scarcity. For the time being, global food production exceeds global demand, and yet, nearly a billion people are chronically hungry. For many poor populations, global food supply is irrelevant because they do not have the resources to access global grain markets. For them, meeting nutritional requirements is based on locally productive ecosystems providing sources of basic nutrition. When these systems become less productive as a result of increasing water scarcity, land degradation, or nutrient depletion, the impacts may be quite immediate. Poor, rural, populations are unable to insulate themselves from these changing environmental conditions by accessing global grain markets or importing water or nutrients in the form of irrigation and fertilizer. As a result, these people feel the loss of ecosystem services most acutely. Thus, the scale of inquiry is important to consider with respect to assessing this relationship. Global or national agricultural data may not reflect a particular region's vulnerability to malnutrition as a result of local environmental change. In addition, other factors may come into play. For example, the relationship between degradation of arable land, food supply, and malnutrition may not be linear. The effect may be lagged in time, and subject to a threshold phenomenon: only after agricultural productivity falls below a certain level do communities experience the health effects of declines in productivity. Thus, the analytical approach is important to consider in order to take these distortions into account.

In the more developed regions of the world, access to global markets plays the role of an insulating factor preventing communities from experiencing health impacts of the destruction of ecosystem services. In the words of Sieswerda et al., "Our results suggest that there is a separation of consumption from consequence," (Sieswerda et al. 2001). Of course, if enough pressure is placed on productive landscapes at a global scale then people from all regions will feel the impact.

## *Fresh Water Supply*

The fresh water that humans depend on flows directly from ecosystems, which provide water for extractive and in-stream use, for water-related cultural services, and for other water-related supporting services (also see chapters 6–9, this volume). "Extractive water supply" is that water available for municipal, agricultural, commercial, industrial, and thermoelectric power use. Ecosystems can act as natural water purification plants, filtering out the chemicals, microbes, nutrients, salts, and sediments that contaminate surface and groundwater. They can also buffer extreme water flow events. Intact forests and riparian buffers promote the transfer of surface water to groundwater by infiltration, which reduces flood peaks and can increase base flow, generally increasing the predictability of water availability. Floodplain wetlands also reduce flooding by absorbing and slowing floodwaters (Brauman et al. 2007). Riparian forests, upland forests, wetlands, and mangroves, all of which play a disproportionate role in the provisioning of these hydrological services, are particularly vulnerable to human interventions.

Water availability is a function of factors such as regional climate patterns and natural hydrological processes, and is increasingly affected by anthropogenic impacts, such as climate change, loss of vegetation, and increased demand. Because of these stresses, one-third of the world's population now lives in countries experiencing moderate to high water stress (Corvalán et al. 2005). During the next 50 years, water demand for irrigation – which accounts for roughly 70% of total fresh water use – is expected to triple while household and manufacturing uses are also expected to increase significantly (Postel 1998).

Over a billion people do not have access to adequate safe water and 2.6 billion people do not have access to adequate sanitation (United Nations Development

Programme (UNDP) 2006). Water supply is known to be an important factor in reducing the incidence of waterborne disease (Fewtrell et al. 2005), and inadequate access to water, sanitation, and hygiene is estimated to cause 1.7 million deaths annually and the loss of at least 50 million healthy life years. Half of the urban population in Africa, Asia, Latin America, and the Caribbean suffers from one or more diseases associated with inadequate water and sanitation (Vorosmarty et al. 2005). Inadequate access to uncontaminated fresh water is likely to increase exposure to waterborne disease by reducing access to sanitation and increasing direct exposure to pathogens. In addition, as we have discussed, water scarcity is a major threat to agricultural production and is already reducing local food production in certain regions. Altered flow regimes can also lead to injuries and other effects of flooding. But what are the challenges of providing evidence to support these relationships?

*Scale of inquiry* is, once again, a key factor to consider. Water timing, quality, and availability are all highly regional phenomena, and often depend on land management of highly localized watersheds. Extrapolations of local and short-term effects of hydrologic services to larger scales may be flawed because effects observed on small scales are not always seen within an entire basin (Brauman et al. 2007). Additionally, many aspects of hydrologic response are dominated by extreme but infrequent events (Brauman et al. 2007). Thus, care must be taken in defining the *measure of ecosystem services* when considering hydrologic services. Health effects may not be a function of average flows but rather of extreme flows. For example, reviewing almost 50 years of data from the USA, (Curriero et al. 2001) found that 51% of waterborne disease outbreaks were preceded by precipitation events above the 90th percentile, and 68% by events above the 80th percentile.

Several insulating factors confound the relationship between fresh water supply and human health, especially in higher income countries (Fig. 14.1). Infrastructure plays a critical role in insulating populations from declining quality and quantities of fresh water. Highly efficient irrigation technology, water-free sanitation systems, and water filtration plants can all reduce dependence on large amounts of uncontaminated fresh water. Flood control infrastructure can reduce vulnerability to more extreme runoff patterns. Human behavior related to water treatment (boiling, filtering, etc.) can mask the effects of degraded water quality. And, increasingly, water is essentially being imported in the form of grain grown elsewhere (it takes roughly 1,000 tons of water to grow 1 ton of grain). Affluent countries are often net importers of water, which means they may be less dependent on local services but consume more ecosystem services overall than less affluent countries (Brauman et al. 2007). People who lack the resources to engage these different mechanisms are the ones who will suffer the most direct health impacts from deteriorating access to safe water.

## *Protection from Natural Hazards*

Natural hazards can have immediate impacts on human health in the short term, through injuries, drowning, and heat stress (also see the chapters by Rumbaitis del Rio; Ingram and Khazai; and March, this volume). In addition, human communities may experience several longer term health effects from the loss of living shelters, population displacement, chemical and biological pollution of water supplies, degradation of air quality due to fires, exposure to mold as a result of flooding, and mental health impacts from the trauma of the experience. The specific impacts of floods on human health can be related to injuries in the short term and to outbreaks of water-borne, vector-borne, and rodent-borne diseases as well as mental health disorders over the medium and longer terms (Ahern et al. 2005). Ecosystems can reduce human vulnerability to natural hazards in several ways. For example, intact wetlands provide natural water filtering capacity. Coral reefs, vegetated dunes, mangroves, and wetlands buffer the effects of storms on coastal areas. Standing forests can mitigate flooding associated with extreme rainfall events. Environmental degradation, therefore, reduces the capacity of certain ecosystems to serve as a buffer against climate extremes (Corvalán et al. 2005). For example, the 2004 tsunami in Southeast Asia disproportionately affected regions with degraded coral reefs and mangrove forests (Dahdouh-Guebas et al. 2005; Danielsen et al. 2005; Marris 2005; Kunkel et al. 2006), and, in 1998, Hurricane Mitch disproportionately caused landslides in settings of non-terraced farming on steep slopes in Central America (Cockburn et al. 1999). Bradshaw et al. (2007) found loss of natural forests to be correlated with flood risk and severity in developing countries.

In addition, vulnerability to disasters has increased in recent decades. This may be, in part, a result of the growth of human populations in areas that are at greater risk from extreme weather or natural hazards, such as settlements in low-lying coastal areas or floodplains, or in dryland ecosystems at risk of drought. It is also likely a reflection of more frequent weather-related hazards as projected by the Intergovernmental Panel on Climate Change (IPCC) (Schneider et al. 2007). Globally, the annual absolute number of people killed, injured or made homeless by disasters is increasing (Corvalán et al. 2005).

What are some of the barriers to establishing evidence for the ways that intact ecosystems provide protection from the health impacts of disasters? Many insulating factors obfuscate the ways in which environmental degradation affects human communities. Human vulnerability to natural hazards is mediated by a wide variety of factors including where people live, the quality of their housing, disaster preparedness, early warning systems, and environmental conditions (Adger et al. 2005). Infrastructure is of primary importance. Flood control systems can reduce the impact of hydrological peaks. Disaster preparedness measures, such as early warning systems, can also minimize the impact of natural hazards. Housing quality also affects the ability of a community to withstand extreme events. In addition, philanthropic response in the form of disaster relief efforts can conceal the health impacts that might otherwise be experienced as a result of disasters. These types of organizations assuage the short- and medium-term impacts of disasters through the provisioning of food, fresh water, medical supplies, temporary housing structures, and other goods and services. National and international disaster relief organizations can also enforce positive human practices such as water treatment.

Data availability is another big issue. There are limited data available to evaluate the contribution that environmental change has played in increasing vulnerability to fires, floods, storms, tidal waves, landslides or other hazards. For example, the evidence about the health effects of floods is dominated by studies of slow-onset floods in high-income countries that may have little relevance to flash floods and floods in low-income settings. Yet floods with the largest mortality impacts have occurred where infrastructure is poor and the population at risk has limited economic resources (Ahern et al. 2005). The relationship between forest cover and risk of flooding is also debated with respect to extreme events, such as cyclones and typhoons (Laurance 2007). More data are needed to fully understand the relationships between ecosystem degradation, incidence of disasters, and their associated health outcomes.

## Research Agenda

These examples of the relationships between three different classes of ecosystem services and human health illustrate the ways that ecosystem services are interrelated in dynamic and complex ways, and how the causal pathways between ecosystem service production and human health are complex, difficult to quantify, and mediated by a variety of non-environmental influences. These complexities highlight the importance of interdisciplinary partnerships to improve our understanding. If we can better understand the health impacts of the loss of ecosystem services, we will be able to apply this information to guide policy, and to help measure health improvements following the implementation of a new ecosystem services management approach. The MA concludes that efforts "will require an unusual level of interdisciplinary analysis and synthesis in which the population health sciences are central, especially epidemiology."

More clarity is needed on the different intellectual paradigms that characterize epidemiology and ecology, in order to move toward integrating the two fields. In order to be more explicit about what defines health and identify confounding factors in the relationship, ecologists and public health researchers must start to speak a common language. For example, public health scientists should understand that ecologists take offense when "ecological" is used to describe a study's limitations as purely correlational, since much research by ecologists establishes causal mechanism. Ecologists and environmental scientists should take into consideration that "health" comprises many outcomes, with many distinct and multifactorial etiologies. Only when this type of understanding is built can we begin to move forward not only in talking about these issues, but toward building data in support of the relationships in question, and ultimately addressing them with calls to action.

Understanding the complex causal webs and establishing causal inference about the relationship between ecosystem health and human health will require collaborations between ecologists and health scientists, to produce more data, and to carry out more sophisticated analyses that recognize the complexity of the problem. Large country-wide datasets can be used to ask questions about when ecosystems do or do not support community health, but appropriate stratification should be used, as discussed above. For example, a global burden of disease approach can be used to investigate the impact of changes in particular ecosystem services on the incidence of specific diseases in a series of different types of ecosystems and human communities. Several large databases on both human health conditions and ecosystem conditions are available for such an effort. In addition, collaborations between ecologists and health scientists at the time of data collection will improve the ability to provide causal inference. Rather than tacking on health outcomes or environmental conditions as an afterthought, ecologists and epidemiologists can work together to design studies that incorporate aspects of both from the outset. Investigators from different disciplines can work together to develop a conceptual model for how they believe environmental conditions are linked to health outcomes at a specific location before beginning any data gathering activities. The causal pathways that make up such a model can then be tested as hypotheses by gathering the appropriate targeted data.

Ecological data can be incorporated into different epidemiological study designs. *Active surveillance* can be used to monitor both disease incidence and ecological parameters at the same time. *Prospective studies* could be employed to look for expected health outcomes in a population affected by a particular ecosystem management approach (e.g., places where a service will be significantly degraded as a result of planned activity where the consequences of this degradation can be tracked.) *Case–control* epidemiological studies can be used to investigate the particular ecological conditions surrounding a health condition (e.g., places with very similar populations and histories but strongly different ecosystem health (neighboring watersheds) that are managed very differently). Where good historical data exist about both health and ecosystem service changes, *retrospective* studies can explore their relationship in time. Where significant efforts have been made to restore services *intervention trials* can track the health impacts of a restoration project aimed at restoring ecosystem services.

Where traditional epidemiological methods fail, newer approaches have been developed to address the broader contexts that determine population and ecosystem-level health risks. In recent years, many epidemiologists have argued for public health research to move beyond traditional risk factor analysis at the individual level and toward analysis concerned with multiple levels and types of causation. Several more sophisticated approaches have been proposed, such as environmental epidemiology (Pekkanen and Pearce 2001), ecoepidemiology (Susser and Susser 1996), social-ecologic systems perspectives (McMichael 1999), and ecosocial theory (Krieger 2001). These efforts all use a systems theory-based approach to extend the purview of causation across axes of space, time, and organizational level and propose to inter-relate research at different scales through feedbacks and interactions (Eisenberg et al. 2007; Plowright et al. 2008). Multilevel statistical models, and dynamic mathematical models, time-series analysis, panel studies, and risk analysis are all examples of these newer approaches that can be used toward the goal of understanding ecosystem health–human health linkages.

The MA Health Synthesis concludes that "the level of uncertainties and the unsuitability of standard approaches lead many scientists to avoid attempting to answer some questions posed directly by decision-makers. … Scientists tend to respond with a scientifically more rigorous and less uncertain answer to a small part of the equation." More extensive collaborations between ecologists and epidemiologists can help provide rigorous data to fill gaps in knowledge and, at the same time, produce science that addresses policy-makers' immediate concerns.

## Conclusion

In this section, we have seen that large-scale, anthropogenic, environmental changes can cause significant threats to human health. The preceding chapters on the impacts of land use change, disease ecology, and climate change describe how accelerating climate and land use change are likely to impact human health. This chapter describes how many other impacts may be mediated through deterioration of ecosystem services (see Fig. 14.2). In combination, this deterioration is increasing the exposure of hundreds of millions of people to food scarcity, water scarcity, natural hazards, infectious diseases, and population displacement.

For each of these risks, different populations around the world have dramatically different vulnerabilities. In part, this is because the biophysical changes human activity is causing around the planet are not uniform. Rapid glacial melting on the Tibetan plateau threatens dry season water supply for over a billion people living and growing irrigated crops in the river basins of Asia's great rivers. Droughts and increased temperatures caused by climate change in sub-Saharan Africa will interact with existing water scarcity, soil degradation, and nutrient depletion to reduce crop yields and constrain already tight food supplies. The triple threat of more severe storms, rising sea levels, and degraded coastal barriers will pose significant risks to low-lying coastal populations (10% of the human population lives in coastal areas at less than 10 m elevation).

But differential exposure to the biophysical changes associated with human activity is not the only reason why vulnerabilities to these threats will vary across different populations. Vulnerability, as a concept, includes not only exposure to health risks associated with changing environmental conditions but also characteristics of a population that determine its ability to adapt to such conditions. Many of the threats associated with global change can be reduced by means of trade, technology, infrastructure, behavior change, philanthropy, and governance. Populations with the resources (economic and sociocultural) to engage these mechanisms to reduce vulnerability will suffer less than those without such resources (see Fig. 14.2).

There is an urgent need to characterize and quantify these growing threats more accurately. We need to begin modeling each of these types of vulnerability to accelerating environmental change and mapping out which populations are at greatest risk. To do so, will require collaboration from a wide variety of scientific disciplines, and central among them, will be ecology.

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