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Forum

Ecosystem Services Connect Environmental Change to Human Health Outcomes

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Global environmental change, driven in large part by human activities, profoundly impacts the structure and functioning of Earth's ecosystems (Millennium Ecosystem Assessment 2005). We are beginning to push beyond planetary boundaries (Steffan et al. 2015), and the consequences for human health remain largely unknown (Myers et al. 2013). Growing evidence suggests that ecological transformations can dramatically affect human health in ways that are both obvious and obscure (Myers and Patz 2009; Myers et al. 2013). The framework of ecosystem services, designed to evaluate the benefits that people derive from ecosystem products and processes, provides a compelling framework for integrating the many factors that influence the human health response to global change, as well as for integrating health impacts into broader analyses of the impacts of this change.

Information key to assembling the puzzle linking environmental change to human health is typically sealed within academic silos. The ecosystem services framework is useful, first, because it provides a platform for communication across disciplines in the natural, social, and health sciences. Second, the framework is an inclusive and powerful conceptual tool for translating scientific knowledge into actionable policy. Interdisciplinary approaches, like those developed in the field of environmental health, can augment their reach and connections with other disciplines using the ecosystem services framework with a goal of improving understanding and management of emerging health impacts of environmental change. National governments from Belize to Indonesia, companies from Puma to Coca Cola, and land-use managers from the US Department of Defense to individual farmers are using the ecosystem services concept to articulate and quantify their environmental impact (Daily and Matson 2008; Ruckelshaus et al. 2015). Using the common lexicon of ecosystem services can help integrate human health considerations into business and policy decisions that affect environmental conservation and development (Brauman 2015a, b; Polasky et al. 2015).

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From the first discussion of ecosystem services, human wellbeing has been broadly defined to include human health (Millennium Ecosystem Assessment 2005). In practice, however, health outcomes have been integrated into ecosystem services assessments in a limited way (Myers et al. 2013; Sandifer et al. 2015). Most existing ecosystem services assessments evaluate a patchwork of goods and services important to human wellbeing, ranging from increases in recreational value to cost savings at water treatment plants, but do not consider health implications (Costanza et al. 2014; Brauman 2015a, b; Keeler et al. 2012). Nevertheless, there is growing demand for more robust and comprehensive assessments of human health implications of environmental change (Daily and Matson 2008; Myers et al. 2013). For instance, the 2015 Convention on Biological Diversity publication "*Connecting Global Priorities: Biodiversity and Human Health, a State of Knowledge Review*" explicitly states that, despite the clear role that ecosystems and biodiversity play for human health, that link is not being made in policy forums (CBD and WHO 2015).

Expanding the study of ecosystem services to truly incorporate health impacts, in part by improving communication within environmental and human health disciplines, can ultimately better inform policy decisions and improve our ability to manage the health impacts of environmental change. Economic analyses of ecosystem services, which can include economic valuation of human health, have been both criticized and defended (Norgaard 2010; Farley 2012). Ultimately, economic valuation and human health are not mutually exclusive. To truly understand the implications of global change for human health, and for health to be properly valued in the wide range of practices adopting the ecosystem services framework, the environmental health community must engage directly with ecosystem services, and improve its implementation. Here, we illustrate how the ecosystem services framework can be used to foster cross-disciplinary connections and describe the impacts of environmental change on human health (Fig. 1).

The Challenge of Linking Environmental Change to Human Health Outcomes

The links between environmental change and human health outcomes are varied and complex. Many of the ways people change the environment are intended to improve health, such as those designed to secure food, including conversion of grasslands and forests for agriculture, or to reduce communicable disease, including wetland drainage to control malaria vectored by mosquitoes. Such activities, however, can also lead to unintended, negative health outcomes. Conversion of forest to agriculture may augment food availability while increasing habitat for disease-causing

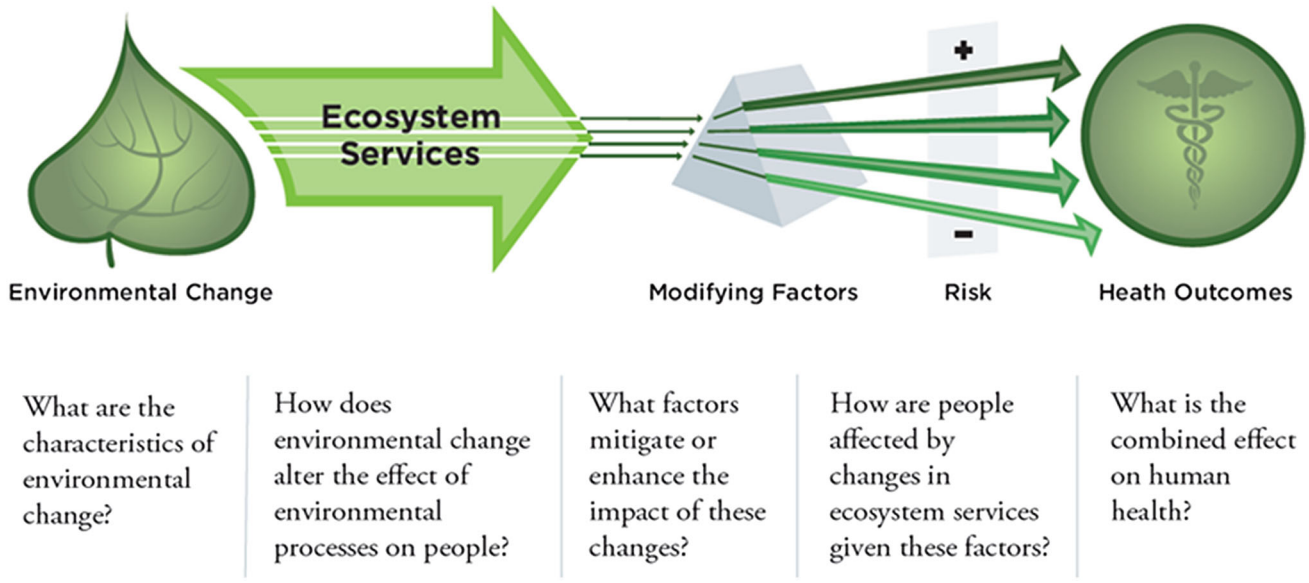

Figure 1. Conceptual framework for linking environmental change to human health outcomes using ecosystem services.

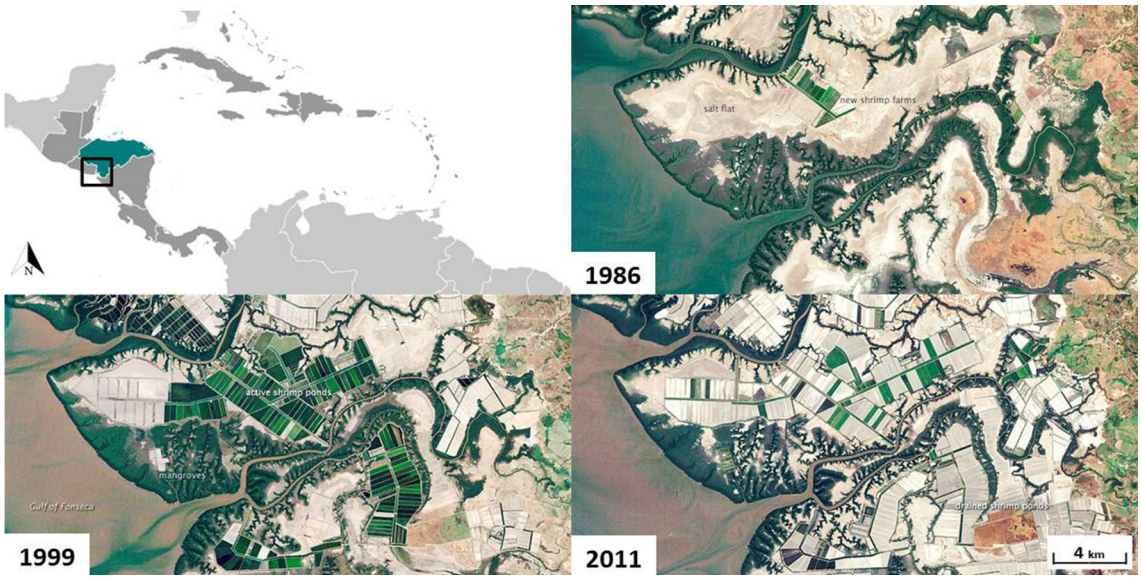

Figure 2. The impact of shrimp aquaculture and ecosystem management on coastal mangroves. Tidal salt flats (*beige/gray*) are replaced with shrimp farms (*green/gray rectangles*), resulting in increased crowding of aquaculture practices against coastal mangroves (*dark green*) in some locations. Gulf of Francesca, Pacific coast of Honduras and Nicaragua (NASA Earth Observatory) (Color figure online).

mosquito species (de Castro et al. 2006). Drained swampland may reduce vector-borne disease risk but simultaneously amplify the vulnerability of communities to deadly coastal storm surges (Das and Vincent 2009). Integrating and quantifying the full range of impacts, particularly unintended negative impacts, is crucial to environmental management that improves human wellbeing.

The ecosystem services framework presented here provides guiding questions derived from shared aspects of existing ecological and health research frameworks. The ecosystem services framework can link researchers from disparate disciplines and connect research findings to policy action. Generality is crucial, because while researchers from many fields have begun describing specific connections between human health and environmental change (e.g., infectious diseases, Eisenberg et al. 2007), those linkages and the frameworks developed to understand them have not been widely adopted outside of specialized subfields (e.g., disease ecology). The result has been a fragmentation of empirical evidence and lack of integration across disciplines in both the natural and social sciences, culminating in a failure to incorporate key findings from other fields (Myers et al. 2013). Although ecosystem services research is more complex than the framework we present here, the broad guidance the framework provides allows it to encompass a large number of disease-specific frameworks. We hope it will encourage a shift in perception that catalyzes future research approaches.

The ecosystem services framework offers a compelling approach for assessing the net impacts of ecosystem alteration and evaluating the distribution of those impacts (Pagiola et al. 2004; Bonet-García et al. 2015). The degradation, management, and restoration of mangrove ecosystems provide an excellent example of the wide range of pathways by which environmental change influences human health, including via injuries, communicable and noncommunicable diseases, and nutrition. The management, or mismanagement, of these fragile ecosystems has played out visibly on landscapes around the world (Fig. 2), with estimates of over 40 billion dollars in economic damages per year (UNEP and CIFOR 2014). Changes in mangrove ecosystems are often cited as an example of the adverse effects of environmental change (Arkema et al. 2013), largely based on economic impact assessments (Barbier et al. 2011; Vo et al. 2012). We take an approach that expands on previous economic valuations of changes to mangrove ecosystems by including impacts to human health. Using the ecosystem services framework, we show that changes to mangrove ecosystems have diverse effects on human health that are both different from and broader than the economic impacts previously evaluated.

Ecosystem Services as a Unifying Framework

The ecosystem services framework presented in Figure 1 distills many of the core concepts from studies synthesizing potential impacts of environmental change on different dimensions of morbidity and mortality. Each element of the figure coalesces around a general question that researchers from across the natural and social sciences are likely already addressing.

What are the Relevant Characteristics of Environmental Change?

Major disconnects between studies of environmental change and studies of human health can occur when they monitor variables that cannot be linked to one another via the mechanistic processes. Nutritional deficiencies, vector-human contact and natural disasters will occur regardless of ecosystem condition. Establishing a relevant baseline of human health and of an ecological state against which to judge the impact of ecosystem change is critical.

Mangrove root structure, for example, is the critical factor affecting fish nurseries, and coastal fisheries may decline even if mangrove area is maintained if mangrove structure is altered (Mumby et al. 2004). Monitoring mangrove extent is thus insufficient to link ecosystem change to nutrition. Similarly, mosquitoes that serve as vectors for malaria and other diseases are endemic in many places where changes to mangrove ecosystems are occurring. Attributing changes in vector abundance to changes in mangrove structure requires comparison against a baseline level of vector abundance given natural wet–dry cycles (Jacups et al. 2012).

How does Environmental Change Alter Ecosystem Services?

There are discernible mechanisms by which ecosystem processes affect health outcomes. These connections are the hub of the conceptual framework illustrated in Fig. 1. The Millennium Ecosystem Assessment organized ecosystem services into four general categories, each of which describes ecological processes that can be connected to human health outcomes: (1) provisioning services, such as food production for nutrition; (2) regulating services, through which ecosystems affect natural processes like vector-borne disease transmission or exposure to natural hazards; (3) cultural services, including recreational or psychosocial benefits derived from the environment; and (4) supporting services, which are not directly used by people but are instrumental in the delivery of other services; soil formation, which underpins the provisioning service of food production, is an example (Millennium Ecosystem Assessment 2005).

Mangrove ecosystems provide a suite of services in all of these categories, many of which can be altered by human activities in ways that impact health (Horwitz and Finlayson 2011). Nutrition is an example of a provisioning service: mangroves maintain critical habitat for juvenile fish that are vital to both local subsistence and commercial fishers. Mangrove destruction can lead to a decline in fish production, ultimately affecting nutrition in associated communities (Naylor et al. 2000). Disease transmission is an example of a regulating service: within mangrove swamps, the natural wet–dry cycle that creates and limits mosquito habitat, and thus affects disease transmission, can be disrupted by increased waste- and storm-water run-off from nearby residential or commercial development (Jacups et al. 2012). Protection from storm surges is an example of a different type of regulating service: in the absence of intact coastal mangroves to attenuate waves, loss of life from coastal flooding may be significantly increased (Das and Vincent 2009).

What Factors Mitigate or Enhance the Impact of Ecosystem Changes?

Attributing changes in health (e.g., nutritional deficiency, vector-human contact, or injury due to natural disasters) to environmental change is complex because human health is a function of much more than just ecosystem condition. In general, mechanistic studies of environmental change and health have focused on measures of change to risk factors (e.g., forest fragmentation and increased insect vector abundance). Risk is an important determinant of health, but ultimately it is not a health outcome and does not always correlate directly with changes in measures of morbidity and mortality. Individuals and societies have varying capacities to modulate impacts to health, so documenting environmental change and the mechanisms by which it might affect risk is inadequate for understanding and predicting health impacts (Myers and Patz 2009; Myers et al. 2013). It is crucial to identify and account for the human behaviors, social institutions, and physical infrastructure that act as modifying factors that alter the health

impacts of environmental change (Myers et al. 2013). The interaction between these modifying factors and changes in ecosystem services are often very complex, operating in nonlinear or bi-directional feedback loops across different scales of space and time (Adger et al. 2005; Kennedy and Cheong 2013; Myers et al. 2013), yet, to accurately assess the impact of environmental change on human health, they must be accounted for.

Degradation of mangrove forests may reduce the ability of these ecosystems to provide for certain aspects of human health. *Mitigation* of the loss of these services may occur through dietary supplementation with nontraditional food items, uptake of vector-borne disease prevention behaviors (e.g., bed nets, antimalarial medications), or construction of storm walls. When access to mitigating factors is limited or when human behavior *enhances* the risk of a negative health outcome, people are likely to be more sensitive to ecosystem alteration. Thus, in order to evaluate whether mangroves buffer communities from coastal storm surges, it would be important for a researcher to control for modifying factors by, for example, comparing expected mortality for socioeconomically similar regions with and without mangrove buffers (Das and Vincent 2009). This would make it possible to attribute human health outcomes to ecosystem services provided by mangroves rather than to the extent of community disaster preparedness efforts.

What is the Combined Effect on Human Health?

The specifics of environmental change, the impact on ecosystem services, and consideration of modifying factors are integrated by this question. Health is a fundamental component of human wellbeing, inherently multi-dimensional, and exists along a somewhat subjective continuum from poor to good. The public health and medical communities have developed a variety of metrics for measuring the net impact of factors related to health across individuals or groups (e.g., disability-adjusted life years [DALYs] quantify the number of years of healthy life lost to disability and disease, Murray et al. 2012), and it is possible to put an economic value on these metrics (Whitehead and Ali 2010). Integrated metrics of health, whether in life years or economic terms, allow the net impacts of environmental change to be evaluated. It is crucial, however, to undertake the difficult task of determining *whose health* is ultimately affected (Myers et al. 2013).

When mangroves are altered by human activities, different groups will experience a range of health impacts and will have varying capacities to adapt. For some, ecosystem-change-driven impacts to health will be negative and may even compound one another. For subsistence fishers, for example, a decline in fisheries would reduce nutritional intake and diversity. Those who cannot compensate through employment in aquaculture, for example, may not be able to replace this nutrition source, or they may rely more heavily on processed food items, leading to increases in obesity and related chronic diseases (Snowdon et al. 2010). Declining nutritional status may have a cascading effect, making this group more susceptible to other diseases (Caulfield et al. 2004). For other groups, ecosystem change may improve health directly or provide access to mitigation strategies that were previously unavailable. Those who own or work at shrimp farms that replace mangroves, for example, may see their food security improve and their ability to purchase bed nets or antimalarial medications increase as income increases. As this group becomes less susceptible to the risks posed by ecosystem change, they may become more likely to allow such changes to occur. The net health impact to the community as a whole depends on the distribution of health costs and benefits across distinct sub-communities with a range of exposures, mitigation capability, and baseline health.

A Call to Action

The ecosystem services framework has been successful in integrating environmental concerns into policy decisions, at least in part because economic valuation allows environmental impacts to be integrated into traditional policy tools such as cost–benefit analysis (Mace 2014). However, these assessments generally have not considered either net effects to health associated with ecosystem change or where the burden of disease is ultimately felt (Myers et al. 2013). There is growing interest in the health sciences to incorporate the synergistic effects of multiple diseases and the bio-social context with which they occur (e.g., mental health and HIV/AIDS syndemic) (Singer and Scott Singer and Scott 2003). Integrating multiple health impacts into ecosystem services assessments is a crucial next step in quantifying the impact of environmental change on human wellbeing. Doing so may illuminate opportunities to improve environmental management to mitigate some health impacts. For example, if drainage channels are designed to maintain natural hydrologic cycles when aquaculture expansion occurs, coastal fisheries and thus fisher food

security would still decline, but the burden of malaria would not increase.

Using the ecosystem services framework can also improve communication among researchers within and beyond fields associated with health sciences. Although the ecosystem services framework is inherently interdisciplinary, a substantial body of research to date is not yet truly integrative (Brauman 2015a, b). To improve human wellbeing, the ecosystem services approach must incorporate human health, and do so in an interdisciplinary way. We call upon diverse researchers and policy makers to use the ecosystem services approach to unify the study of environment–human health linkages. Our mangrove example alone requires collaboration among (roughly following Fig. 1, left to right): geographers, land-use scientists, bio-geochemists, ecologists, resource economists, behavioral scientists, hydrologists, veterinarians, disease ecologists, epidemiologists, and others. A robust and accessible framework of the kind provided by ecosystem services allows for whole-system understanding and knowledge sharing.

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