Human–environment interactions in population and ecosystem health

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As the global human population continues to grow, so too does our impact on the environment. The ingenuity with which our species has harnessed natural resources to fulfill our needs is dazzling. Even as we tighten our grip on the environment, however, the escalating extent of anthropogenic actions destabilizes long-standing ecological balances (1, 2). The dangers of mining, refining, and fossil fuel consumption now extend beyond occupational or proximate risks to global climate change (3). Among a plethora of environmental problems, extreme climate events are intensifying (4, 5). Storms, droughts, and floods cause direct destruction, but also have pervasive repercussions on food security, infectious disease transmission, and economic stability that take their toll for many years. For example, within weeks of the catastrophic wind and flood damage from the 2016 Hurricane Matthew in Haiti, there was a dramatic surge in cholera, among other devastating repercussions (6, 7). In a world where 1% of the population possesses 50% of the wealth (8), those worst affected by extreme climatic events and the aftermath are also the least able to rebound.

Compounding the impact of natural disasters, our progressively more intimate interactions with fragmented environments (9) have given rise to an era of disease emergence and re-emergence at unprecedented rates, as exemplified by recent outbreaks of the Ebola and Zika viruses. Furthermore, globalization to an extent that includes the airline travel of over eight million people every day has enabled such disease outbreaks to disseminate rapidly and pose a threat far beyond their areas of origin (10). Addressing these challenges requires an understanding of coupled human–environment dynamics, whereby human activity modifies an environmental system (often detrimentally), and the resulting environmental repercussions then impact humans. In turn, these impacts can potentially spur a shift in human activity toward protection and restoration. For example, Lubchenco et al. (11) describe how overfishing has led to plummeting species diversity and abundance in ocean ecosystems. Recognizing these untenable practices, steps were taken to incentivize sustainable consumption that achieved the rebound of fish populations. Human–environment systems are not just complex and coupled, but also adaptive, in that human response to calamities can help restore environmental sustainability (12, 13). Sustainable and equitable solutions are required to address the interconnected challenges of protecting the health of the natural environment and protecting the health of human populations. Determining solutions that optimize trade-offs between short-term and long-term objectives of resource consumption and sustainability requires analyses of the multilayered interconnectedness of environmental, social, epidemiological, and political systems.

This collection of papers builds on recent momentum in the development and implementation of transdisciplinary collaborations that simultaneously consider human, nonhuman, and environmental health and the nonlinear relationships between them. The studies illustrate myriad applications of cross-sectoral approaches in coupled human–environment systems to solve public health and environmental conundrums. They underscore the importance of complex ecological interactions for these issues, as well as advance methodologies to integrate the complexity of human–environmental systems into analyses that underlie effective solutions.

Governance Considerations

The equilibrating processes that buffer the effects of the burgeoning human population density are extracted from a diminishing area of global natural environments that supply the air we breathe, the seafood we consume, and the land we cultivate. Many of these environments provide resources that are shared by multiple governing states and have influences beyond country boundaries. Perhaps the greatest barrier to protecting these environmental systems is the temptation of states

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or other stakeholders to contribute to a "tragedy of the commons," wherein a common resource is overexploited because stakeholders with unfettered access have an incentive to exploit the resource as quickly as possible before the other stakeholders do the same (14, 15). Guarding against exploitation requires a system of governance, whether collectively imposed by the stakeholders or externally imposed (14, 15). Common pool resource problems necessitate considering strategic interactions in a group, as can be formalized and analyzed using game theory. Using game theory, Barrett (16) outlines three forms of international law that can be used to circumvent environmental degradation: (*i*) treaties that implore states to act in a collective interest; (*ii*) treaties that impel cooperating states to punish the uncooperative; and (*iii*) treaties that coordinate the behavior of states. Noting the failures of the first two forms, Barrett applies game theory to demonstrate elegantly the potential for "coordination games" to ensure cooperative protection of our shared global environment. Barrett details how effective cooperation can be facilitated both by international policy that coordinates all governing parties to realize mutual gains, and by trade agreements or technical standards formulated such that all parties can coordinate in their own interest to realize mutual gains.

The failure of international treaties with weak accountability is highlighted by Mangel (17) in the specific context of whaling. Simultaneously, Mangel underscores the complexity of enforcement, which entails a role for evidence-based scientific expertise at the interface of law and species preservation. Similarly, Castro et al. (18) call for engagement of the academic community at the corporate interface to assess objectively the complex impacts of the industrial activities. Analogous to the conflict between governing states over shared resources highlighted by Barrett (16), conflicts similarly arise between corporations and communities, as illuminated by Castro et al. with case studies from extractive industries and hydropower development. Castro et al. (18) also highlight a particularly vexing long-standing issue: the problem of obtaining unbiased environmental, social, and health impact assessments for corporate projects where the results of the assessments influence decisions on whether or not a project is to move forward. Furthermore, follow-up impact assessments, confirming or overriding the impact predictions, are also needed to form a basis for corporate accountability once project implementation is underway. An important and balanced framework for this process comes from an unexpected source: the Roman Catholic Church in several sections of the Papal Encyclical (19–22) "Laudato Si," recently issued by Pope Francis. Operationalization of the segment of the encyclical devoted to "Environmental Impact Assessment" is a major challenge, where success could have profound positive impact on human–environmental interactions.

Among natural resources that are shared among states, ocean ecosystems are one of the most prominent. The essential roles that ocean ecosystems play in food security, economic development, and climatic processes led the United Nations Sustainable Development Goals to include the conservation of marine reserves as an explicit priority for their most recent agenda. Hurdles to this conservation include overfishing, climate change, and population growth, all of which are captured and addressed by the complex adaptive-systems framework advanced by Lubchenco et al. (11), which demonstrates how complexity can be navigated to generate thoughtful incentive structures that align conservation and economic benefits. Lubchenco et al.'s framework can motivate positive shifts in behavior at the individual, corporate, or national level, as illustrated by recent progress toward fishery restoration. In a contrasting example of unsuccessful incentive structures, Walsh and Mena (23) examine how policies surrounding ecotourism within the iconic haven of the Galapagos have been heavily weighted toward supporting the growth of tourism, benefiting the local economy at the expense of environmental decay. Reforming incentive structures simultaneously to promote human well-being and alleviate inequalities across and within nations, both in the near and longer-term, has the potential to resolve the conflicts described in the Galapagos by Walsh and Mena (23), in the extractive industries by Castro et al. (18), and in Japanese whaling practices by Mangel (17).

Monitoring and Modeling Human–Environment Feedbacks for Ecological Resources

One of the greatest challenges facing humans is how to feed our growing population while sustaining what remains of biodiversity and ecosystem services. Conversion of natural areas to agricultural use is the leading cause of forest loss globally. Natural grassland areas are under even greater threat (24). Two papers in this issue examine the power of applying new monitoring tools and modeling approaches to conserve biodiversity in agriculturally dominated ecosystems. Mendhenhall et al. (25) assess a region in Costa Rica across which nearly 50% of forest cover is embedded in rural agricultural land. The preservation of forest thus requires that diverse farming systems that preserve biodiversity be highly valued by the land owners. To determine the ecological value of arboreal and agricultural coexistence, Mendenhall et al. develop models that quantify the relationships between local tree cover and biodiversity. They stress the importance of compensating farmers for the ecosystem services provided by their lands, another example where the architecture of incentives is crucial to the sustenance of ecosystem health and viability in coupled human–environment systems. Similarly, Henderson et al. (26) examine a region in southern Brazil where natural mosaics of forests interspersed with grasslands are gradually converted to agricultural and silvicultural use. The authors study long-term trajectories of these mosaics by coupling the ecological dynamics to a model of human behavior, calibrated with ecological and sociological data. Henderson et al. show that the sustainability of forest–grassland–agriculture mosaics depends on a comprehensive valuation of land-use types that includes both economic and ecological dimensions, a theme that is underscored by a number of papers in this series.

Technological innovations promise transformation of our lives and economies, but innovations can concurrently destabilize our natural environment. As just one example, hydraulic fracking facilitates the extraction of otherwise inaccessible fossil fuel and has been credited with catalyzing the economies of a number of US states following financial crises. Nevertheless, the staggering costs of air pollution, drinking water contamination, and global warming exacerbation are unacceptable. Sustainable environmental equilibria can be subject to sudden and catastrophic regime shifts that could arise from technological innovations that accelerate the rate at which resources can be extracted. The detection of early warning signals is a vital component of adaptation strategies that mitigate environmental disruption. Bauch et al. (27) demonstrate that coupled human–environment systems can also exhibit the same types of early warning signals that occur in uncoupled ecological systems. Important differences arise, however. For example, early warning signals could herald shifts toward either collapse or conservation regimes, depending on parameter values. Moreover, human vacillation between complacency and concern in response to perceived resource availability can threaten the viability of long-term conservation and keep the human–environment system perpetually in the vicinity of a dangerous tipping point. This danger underscores the need for long-term thinking to replace reactionary behavior. Hastings (28) emphasizes the importance of considering short- and long-term temporal dynamics, including time delays and tipping points that arise from population demography, in the recovery of ecological systems under alternative management practices. The time scale pertinent to optimizing outcomes of management and sustainability is highly dependent upon the specific ecological system in question. Hastings provides a broadly applicable optimization approach that addresses the issue of time scale for environmental management, ranging from invasive species to fisheries.

Human–Environmental Health

The field of epidemiology is rooted in ecological theory. The principles of species conservation are fundamental to infectious disease epidemiology, except the goal is reversed: we aim to push a pathogen species to extinction. The increasingly mobile and dense human population represents a continuously expanding niche for infectious diseases. Similarly, agricultural and domestic animal species have increased alongside humans, whereas most other species have declined. To an impressive extent, we have been able to keep pace with pathogen emergence and spread by virtue of our ingenuity, underlying the development of vaccines and therapeutics. Nonetheless, pharmaceutical innovations are only as effective as the degree to which humans are able and willing to adhere to the recommended implementation. Vaccine refusal has plagued the control of childhood disease and eradication efforts against polio (29). Also critical is population adherence to nonpharmaceutical interventions, such as animal movement bans during the United Kingdom foot-and-mouth outbreak and avoidance of the culturally important traditional burials during the West African Ebola outbreak.

Frameworks, such as the one developed by Lubchenco et al. (11) to facilitate the alignment of otherwise opposing interests and enhance synergies between disparate entities in fisheries, are equally important to the arena of public health. The unifying One Health paradigm incorporates the human species as a component in an interdependent health ecosystem, where we can both affect and be affected by changes in the environment and in zoonotic communities. Within our lifetimes, we have seen HIV and Ebola jump from primates to humans, as well as antimicrobial resistance spread in response to our livestock care practices. Beyond these high-profile recent examples, many of history's greatest scourges originated via zoonosis, including rabies, leprosy, and the bubonic plague. The One Health movement seeks to make the human connection to other species an explicit part of analysis and planning. In support of this paradigm, governmental agencies and academic organizations have devised a variety of ways for uniting expertise across traditionally separate fields, usually by economic quantification of projected costs and benefits. For example, the Indian state of Tamil Nadu has pioneered the establishment of a state-level One Health coordination committee. This committee brings together leaders from the human health, veterinary, and animal welfare sectors to develop rabies control strategies that transcend sectoral boundaries. To inform cooperative resource allocation and decision-making, Fitzpatrick et al. (30) were commissioned to evaluate the various strategies under consideration by this committee, quantifying the impact of veterinary sector efforts on human health. In comparison with economic analyses of rabies campaigns in sub-Saharan Africa, the vaccination coverage found to be effective and efficient for Tamil Nadu was also highly feasible to implement, even more so than rabies control strategies advocated by the World Health Organization and implemented in other countries. The case study of rabies control in Tamil Nadu demonstrates the value of even modest investments in zoonotic disease prevention, and highlights the importance of tailoring infectious disease control policies to specific settings. At the same time, Fitzpatrick et al.'s framework for the evaluation of the effectiveness and cost-effectiveness of One Health strategies is applicable to other multisectoral solutions to address public health and environmental challenges.

A controversial ethical issue underlying cost-effectiveness analysis specifically, and resource allocation trade-offs between different points in time generally, is the rate of discounting the future that should be applied to integrate both costs and values over time, given both uncertainty about future events and the opportunity costs from forgoing alternative investments. For considerations of health economics, the World Health Organization stipulates that a 3% annual discounting rate should be applied (31). This has become the standard in cost-effectiveness. However, compounding of the 3% discounting every year leads to diminishingly small valuation for the future beyond a couple of decades. This low valuation stands in contrast to the degree of concern that most people feel for the future that their children and their children's children will experience. It has been argued that for environmental considerations, the discounting rate that is ethical to future generations should be extremely low, to properly treat the interests of future generations (32).

Economic discounting is partly motivated by the uncertainty of what the future holds. Mechanistic and statistical models are often developed with the goal of predicting future trends in human–environment systems. The focus of several papers in this issue was predictive modeling, particularly how the interrelated dynamics of disease transmission and human behavior influence the ecology, evolution, and control of infectious diseases (29) across spatial, temporal, and organizational scales. Using a model of intrapatch disease spread and interpatch mobility, Castillo-Chavez et al. (33) illustrate the limitations of existing theoretical frameworks with respect to modeling such complex adaptive systems. The authors call for the formulation of improved theoretical frameworks that can encompass such processes and disentangle the role of epidemiological and socio-economic forces.

Although there is overwhelming evidence for anthropogenic climate change, the multilayered repercussions on physical and biological systems are likely so extensive that they are still being realized. As an example of this concern, Fisman et al. (34) identify externalities of climate change on disease trends in the United States that have previously gone unappreciated. Specifically, their analysis of temporal trends of hospitalization data reveals that vector-borne and enteric disease in the United States are impacted by climatic shifts associated with El Niño Southern Oscillations. Given that this relationship between climate change and vector-borne, as well as enteric diseases, is significant even in a country with high levels of sanitation and relatively low prevalence of these diseases, the influence of climate change on such diseases are expected to be even greater in developing countries. Becker et al. (35) point out that modeling-coupled human–environment interactions requires understanding how natural system dynamics unfold at both small and large spatial scales, such as individual households versus entire cities. Applying a stochastic disease transmission model to a 1904 measles outbreak in London, as well as to the 2014–2015 Disneyland, California measles outbreak, Becker et al. find that disease transmission within schools and within age classes is higher than has been estimated from population-level serological analyses.

Population dynamics not only vary at different spatial scales, as in Becker et al. (35), and at different time scales, as in Hastings (28), but can also be affected by rapid evolutionary processes. Lewnard and Townsend (36) demonstrate that the evolution of disease resistance in a disease vector can drive shifts in outbreak seasonality. To capture these complex interactions, they analyze extensive data from the Indian Plague Commission on climate, rat infection and resistance, and survival of flea vectors at different temperatures. Integrating this data into a model that combines environmentally forced plague dynamics with selection for a quantitative resistance trait in rats, Lewnard and Townsend demonstrate that the observed phase shifts in epidemic dynamics were modulated by the evolution of resistance over time. Moreover, incorporating the evolution of plague resistance among rats into their model reproduces observed changes in seasonal epidemic patterns. Furthermore, it captures experimentally observed associations between climate and flea population dynamics in India. Similar to Becker et al. (35), Lewnard and Townsend (36) demonstrate that historical datasets can yield insights into the epidemiological, ecological, and evolutionary dynamics of re-emerging disease agents, insights that will help to guide the design of preparedness and response strategies that mitigate future outbreaks.

The Need for Cooperation in Protecting Human–Environment Systems

Fragile ecosystems are subject not only to conflicts between short-term rewards and long-term conservation goals, but also are subject to the vagary of human responses to environmental challenges. Given that many environmental problems—including those explored in this issue—represent a common pool resource problem (14), their solution will require improved cooperation between humans. The human mind has spent most of its evolutionary history in a hunter-gatherer setting, and it is in this localized setting that our penchant for cooperation evolved. Consequently, a pressing challenge for the current phase in the evolutionary journey of our species is to promote the scale-up of cooperation far beyond localized settings.

Cross-sectoral, collaborative, and integrated approaches can be powerful tools to bolstering the sustainability, resiliency, and equitability of natural resources within and between generations globally. Public health, conservation, agricultural security, and economic development are deeply intertwined in ways that are not immediately obvious. Understanding the interplay is fundamental to the development of an architecture of incentives and rewards that aligns disparate interests to optimize outcomes over the long-term. In the precarious balance between improving the standard of living across the globe while minimizing the negative externalities associated with the resources that we extract to do so, it is imperative to identify synergies that make effective solutions cost-effective as well. The human species has unparalleled capacities of ingenuity, foresight, and compassion that can be used to direct the current trajectory of the world's ecosystems from rapid deterioration and destabilization toward equity and sustainability.

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