Assessing ecosystem health

D.J. Rapport, R. Costanza and A.J. McMichael

There is now abundant evidence that many human-dominated systems are accumulating various biophysical systems at regional and global levels, and have become highly stressed and dysfunctional. The ‘services’ provided by these ecosystems are essential to human welfare. LA. Stressed ecosystems have become highly degraded, they have also become incapable of supplying services to the same level as in the past. The capacity of the environment to sustain economic activity and human health is, therefore, being reduced. Ecosystems will continue to degrade under pressure of increased demands unless we apply preventative and restorative strategies to achieve the health and integrity of regional ecosystems. This was one of the main objectives outlined in the Rio Declaration on Environment and Development. Principle Seven reads ‘States shall cooperate in a spirit of global partnership to conserve, protect and restore the health and integrity of the Earth’s ecosystems. In view of the different contributions to global environmental degradation, states have common but differentiated responsibilities’. Many of the earth’s ecosystems are ‘unhealthy’. Their functions, particularly those that are vital to sustaining the human community, have become impaired. An ‘ecosystem distress syndrome’ (EDS) is widely prevalent in both aquatic and terrestrial ecosystems. Linking ecosystem health to the provision of ecosystem services (those functions that are recognized as satisfying human needs) and determining how ecosystem dysfunction relates to these services are major challenges at the interface of the health, social and natural sciences.

Ecosystem health from a biophysical perspective

The notion of ‘health’ has generally been used to denote the vitality of individuals and, more recently, of populations (humans, domesticated animals and wildlife). The extension of health to describe regional ecosystems is a response to the accumulating evidence that humans-dominated ecosystems have become highly dysfunctional. Extending the notion of health to regional levels (ecosystems, catchment areas, basins and landscapes) provides new opportunities to integrate the social, natural and health sciences. What is needed are methods for identifying dysfunction and evaluating causes and potential solutions.

Definitions of ecosystem health have been closely allied with the concepts of stress ecology, which define health in terms of ‘system organization, resilience and vigor, as well as the absence of signs of ecosystem distress’. The definition also includes the presence of essential functions and key attributes that sustain life systems (Box 1).

A healthy ecosystem is defined as being ‘stable and sustainable’, maintaining its organization and autonomy over time and its resilience to stress. Assessment of these properties in large-scale systems through specific indicators of resilience, organization and vigor has been attempted for the Chesapeake Bay (USA) and other marine ecosystems, freshwater ecosystems, forested ecosystems, arctic ecosystems and grasslands. Box 2 and 3 illustrate some of the relationships between biophysical change and societal goals and human activities with three case studies drawn from contrasting ecosystems. In each example, stress has resulted in biotic impoverishment, impaired productivity, altered biotic composition to favor opportunistic species, reduced resilience, increased disease prevalence, reduced economic opportunity and risks to human and animal health.

Socioeconomic consequences

The existence of multiple dynamic semistable states for natural and human-dominated ecosystems complicates the task of determining the extent to which ecosystem structure and function have been altered by human activity. However, careful studies leave little doubt that degradation has occurred in many ecosystems, including forests, marine systems, agroecosystems and freshwater. Indeed,

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**Box 1. Indicators of ecosystem health**

**Ecosystem health** can be assessed using measures of resilience, vigor and organization:

- **Vigor** is measured in terms of ‘activity, metabolism or primary productivity’. An example of reduced vigor is a US study of the Great Lakes, which is reduced morphological and functional diversity of fish associations that occurs under multiple stressors (Box 3).

- **Resilience** (counteractive capacity), is measured in terms of a system’s capacity to maintain structure and function in the presence of stress. When resilience is exceeded, the system can ‘flip’ to an alternate state. A prime example is the shift from benthic to pelagic-dominated fish associations in the Laurentian Great Lakes Basin (Box 3).

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An important element in the assessment of ecosystem health is the need for an analysis of land-use history. A dominant ecosystem in the Western USA, that of Ponderosa pine (Pinus ponderosa), provides a dramatic example of anthropogenic change on a large scale (as illustrated). Most signs of Ecosystem Distress Syndrome (EDS) are present in stands of Ponderosa pine today. The indicators of ecosystem health include tree density and productivity, nutrient cycles, disease prevalence and the destructive potential of wildfires. Criteria for the successful rehabilitation of the Ponderosa pine ecosystem are based on monitoring for signs of EDS. Preventative approaches to ecosystem health imply more careful attention to stress pressures and devising means to manage these pressures before degradation occurs [a complete diagnosis of EDS relies on both the stress pressures from human activity that are, at times, combined with natural events, and the impacts of ecosystem behavior]. In their study, Yazvenko and Rapport concluded that the stress pressure exerting the most impact on the ecosystem was fire suppression. Ponderosa pine forests have coevolved with the presence of periodic wildfires. With fire suppression, the ecosystem displayed signs of EDS, including decreased productivity and increased mortality of Ponderosa pines, stagnated nutrient cycles, increased ratios and magnitude of pest and disease outbreaks, and the increased destructive potential of wildfires resulting from higher understorey tree densities (thickets). This study reinforces the need to understand vegetation history, in addition to monitoring for signs of EDS, if preventative measures are to be taken before ecosystem degradation becomes irreversible.

Human health: dependency on ecological support

An important effect of ecosystem degradation is an increased risk to human population health. In addition to the familiar toxicological risks resulting from bio-accumulation of toxic substances (e.g., mercury, lead, and organochlorines), there are various less familiar, potentially severe impacts on human population health from global and regional environmental degradation. These health impacts are likely to arise from a variety of types of ecological and social disruption (Table 1). The important concept here is that the environment is the human habitat; it is not merely a potential source of toxicological exposures (each amenable to specific engineering control). Human population health should thus be understood within an ecological framework as an expression of the life-supporting capacity of the environment. Consequently, population health becomes an important criterion of sustainability—one that, over time, signals whether we are satisfactorily sustaining the social and ecological realms.

BOX 2. HEALTH OF A PONDEROSA PINE ECOSYSTEM

<table>
<thead>
<tr>
<th>INCREASED</th>
<th>DECREASED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree density</td>
<td>Rate of decomposition</td>
</tr>
<tr>
<td>Tree mortality</td>
<td>Rate of nutrient cycling</td>
</tr>
<tr>
<td>Fuel loads</td>
<td>Biodiversity</td>
</tr>
<tr>
<td>Fire hazard</td>
<td>Fire hazard</td>
</tr>
<tr>
<td>Rates of disease</td>
<td>Landscape diversity</td>
</tr>
<tr>
<td>Past outbreaks</td>
<td>Aesthetic value</td>
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</tbody>
</table>

Healthy forest ecosystem

Stressed forest ecosystem

Heavy grazing

Fire suppression

Degradation is so large in some regions that whole ecosystems have become endangered. These changes have led to a reduction in the flow of ecosystem services (Fig. 1).

For example, over-harvesting in New Brunswick forests has resulted in a marked reduction in the harvest of commercial timber above a certain size. This necessitated a shift to logging smaller-aged classes and consequently caused an increase in the production of pulp and paper. Similarly, multiple stresses on the Lower Great Lakes Basin (North America) led to sharp reductions in the availability of high-value commercial fish stocks, such as lake trout (estimated by comparing yields in the latter half of the 20th century with historical data). The recognition of the value of ecosystem services depends largely on the extent of environmental literacy. With a high degree of literacy, most ecosystem functions would be perceived, directly or indirectly, to benefit mankind. However, from the public’s perception, some ecosystem services are more important than others. Thus, although biophysical change, from an ecological perspective, appears to be central to the assessment of ecosystem health, the significance of such change depends critically on the implications for ecosystem services.

The services of ecological systems and the natural capital stocks that produce them are essential to the functioning of the earth’s life-support system. They contribute to human welfare, both directly and indirectly, and therefore represent a significant portion of the total economic value of the planet. Because these services are not fully captured in markets or adequately quantified in terms comparable with economic services and manufactured capital, they are often given too little weight in policy decisions. This neglect might ultimately compromise the sustainability of humans in the biosphere. Several studies in the past few decades have tried to estimate the “incremental” or “marginal” value of ecosystem services—the estimated rate of change of value with changes in ecosystem services from their current levels. Combining these studies, the current economic value of 17 ecosystem services was estimated for 16 biomes and extrapolated to estimate a value for the entire biosphere. This value (most of which is outside the market economy) was estimated to be in the range of US $16–54 trillion per year, with an average of US $33 trillion per year. Because of the nature of the uncertainties, this must be considered a minimum estimate. This is in the same order of magnitude as the global gross national product (GNP). Of course, these valuations neither fully encompass the issues of nonanthropocentric values of ecosystems and the ethical implications of different approaches, nor address the complex dynamics of changing ecosystem services.
The life-supporting systems of the biosphere include ma-
rine and terrestrial food-producing systems, wetlands that
maintain water quality, the ecological constraints on infec-
tious disease agents and their vectors, and the buffering
against natural disasters (floods, storms and landslides, etc.)
provided by conserved forests and coastlines. Large-scale
environmental changes occur, such as climate change, land
degradation and biodiversity loss, then we must expect that
the productivity of agroecos-
systems, especially in already food-insecure zones, and hence
might increase regional levels of malnutrition, and disrupt
local livelihoods and communities with the consequent health
risks of displacement and refugee-status.

Changes in biodiversity per se can influence human health
in many ways30. The vector-borne infection Lyme disease,
which is spread by spirochete-infected host ticks, has in-
creased over several decades in northeast USA and in parts
of central–northern Europe. The ticks, which acquire the in-
fection from rodents (Peromyscus leucopus), spend part of
their life-cycle on deer (Odocoileus virginianus). The elimi-
nation of natural predators and recent reforestation of
abandoned farmland (compounded by sylvan suburban liv-
ing) has caused an increase in the USA deer population this
century and, consequently, there is a much increased potential
for human exposure to infected ticks30.

The El Niño event of the early 90’s, initially associated
with drought conditions in the south-west USA, led to a
decline in plant and animal populations, including natural
predators of the deer mouse (Peromyscus maniculatus). The
heavy rains in 1993 resulted in an uncontrolled proliferation
in the deer-mouse population because of a profuse growth
of pinon nuts, one of their food items. These mice harbor a
virus that can be transmitted to humans, causing hantavirus
pulmonary disease41, a disease that has subsequently spread
to many contiguous states and to western Canada.

There has also been a growing interest in understanding
the ecological dimension to cholera, a bacterial disease that
was once viewed simplistically as circulating via infected hu-
man and contaminated drinking water. Recent evidence indi-
cates that aquatic ecosystems provide a natural reservoir
for the bacterium, where it re-
mains dormant in phytoplank-
ton and zooplankton38. The
environmental conditions that
cause algal blooms (such as climate-induced warming of
waterways and their eutrophi-
cation by agricultural and do-
mainic nitrate and phosphate
runoff) and the subsequent proliferation of zooplankton
might therefore act to in-
crease dissemination of chol-
eria into human populations.

We have only recently be-
gin to explore this ecological
dimension to human health. An ecological perspective is
not yet an integral part of the world-view of epidemiologists,
most of whom have a more mechanistic and reductionist
view of the causes of illness and disease. The ecosystem

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Table 1. Mediating processes and potential effects on human health of changes in climate

<table>
<thead>
<tr>
<th>Mediating process</th>
<th>Health outcome</th>
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</thead>
<tbody>
<tr>
<td>Effect on the range and activity of vectors and infected pests</td>
<td>Changes in geographical range and incidence of vector-borne diseases</td>
</tr>
<tr>
<td>Changed local ecology of water-borne and food-borne infectious agents</td>
<td>Changes in incidence of diarrheal and other infectious diseases</td>
</tr>
<tr>
<td>Changed food productivity (especially crops) through climate changes and associated pests and diseases</td>
<td>Malnutrition and hunger and consequent impairment of child growth and development</td>
</tr>
<tr>
<td>Sea-level rise, with population displacement and damage to physical and economic infrastructure</td>
<td>Increased risk of infectious disease, physical injury and psychological disorders</td>
</tr>
<tr>
<td>Modification of production of air pollutants (including pollen and spores)</td>
<td>Asthma and allergies; other acute and chronic respiratory disorders and deaths</td>
</tr>
</tbody>
</table>

*Modified from Ref. 30.

This perspective should also incorporate some of the human-health implications of changing forest conditions.

Ecosystem health has been designated as a 'theme area' within the International Development Research Centre (IDRC) of Canada. This program, which sponsors research in developing countries throughout the world, focuses on the relationships between population growth, resource use, technological advances and human health. Here, the emphasis is on the nature of the relationship between the ecological change and the consequences in terms of economic opportunity, survival of rural communities and sustaining healthy human populations and human communities. The Intergovernmental Panel on Climate Change (IPCC), through its working group on human health, is investigating risks to human health from climate change. These risks include both direct health effects, such as risks to the elderly populations in urban areas caused by an increase in the severity of heat waves, and risks to human health from extreme weather events, such as the ice storms, mud slides and floods experienced in the past few years in North America and Europe. However, a larger category of potential impact reflects the diverse, less predictable consequences of ecological disturbances (Table 1). The IPCC is also beginning to address more complex questions about how other coexistent global changes, such as ozone depletion, land degradation and biodiversity loss, will affect the ecological determinants of human health.

The notion of health is so strongly associated in the public mind with a preferred state, it is especially vulnerable to political manipulation in its applications to the environment. Ironically, further damage to the environment could be done in the name of promoting health. For example, the infamous 'salvage logging rider' legislation of several years ago was ostensibly a response to the forest health crisis. Here, 'unhealthy' was defined as any forest that was affected by natural perturbations, such as fire, windstorm, insects, disease or any other disturbances, or at risk of being so affected in the future. The rider made logging of any such forests compulsory – which, by definition, could include virtually any natural forest in the USA – without any environmental review and was exempt from environmental law. Fortunately, the legislation expired before too much damage was done. However, it is a classic example of how, without significant public education as to what constitutes ecosystem health, the concept remains vulnerable to misguided actions that could, in the name of ecosystem health, contribute to the degradation of ecosystems.

Answering the critics and dispelling the myths

The strongest criticisms of the ecosystem-health approach have, surprisingly, come from ecologists[46–48]. Although much of ecology originated to solve practical problems concerning human interventions on the landscape, some ecologists appear uncomfortable with extending the inquiry beyond the biophysical interactions to areas of societal values and human health. Some view ecosystem health as resurrecting the metaphor of 'ecosystem as organism', an association that has long since fallen out of favor. Those outside the health sciences also tend to limit their view of health perspective is beginning to extend our understanding of the nature and sources of human health and disease.

Fostering transdisciplinarity: ecosystem health in practice

Ecosystem health is as much about implementing strategies in environmental management as it is about fostering a new integrative science[49]. Indeed, these functions go hand in hand. Ecosystem health is now part of a developing curriculum in schools of public health, faculties of medicine and veterinary colleges[50]. Students in these disciplines are learning that human and animal health at both individual and population levels are conditioned by the state of regional systems. Understanding these phenomena requires a broad integration of knowledge across the social, natural and health sciences[51–54].

In the past few years, national and international environmental programs have begun to develop indicators of ecosystem health, largely from biophysical perspectives, but increasingly integrating socioeconomic and human health considerations. One of the leading programs is the collaborative efforts of the Governments of Canada and the USA to assess the state of ecosystem health in the Great Lakes[55]. The strategy includes the development of indicators of stress (particularly pollution from agriculture, industry and human settlements) and ecosystem response. Measures of response include aspects of the physical, biological and chemical environments of the aquatic community, as well as economic opportunity and risk to human health. Achieving the biotic integrity and ecosystem health of this complex system will depend on combining ecological (natural history) aspects, socioeconomic aspects and human health dimensions.

The notion of 'health' is central for the development of comprehensive monitoring of forest ecosystem conditions in the USA. A national forest health monitoring plan was established by the USDA (United States Department of Agriculture) Forest Service in 1993 (in cooperation with the Environmental Monitoring and Assessment Program of the USA Environmental Protection Agency). This program relies on a standard suite of indicators of forest condition, including estimates of tree biomass, understory vegetation diversity, primary productivity, age-class distribution, crown condition, soil nutrient content and disease prevalence. The program tends to focus on the elements of ecosystem health most closely related to the marketable economic utility of forests. The challenge here is to broaden the perspective to incorporate more indicators of forest ecosystem sustainability (resilience) and the impacts of stress on forests in the human communities for whom the forests are 'home'.

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health as ‘objectively’ determined and fail to recognize the role for value judgements, both in the human health context and the ecological context.

Integrative fields such as ecosystem health also go against the grain of quantitative approaches to ecology because, in seeking a holistic perspective, they rely on both quantitative and qualitative information. Bound up in the critiques of ecosystem health are lingering questions as to whether it is possible to integrate knowledge over such apparently different intellectual territories (social, natural and health sciences). Critics might also argue that ecosystems do not possess health attributes at all — that the ecosystem is the sum of the interactions of its components, and therefore the question of health is irrelevant. Finally, some might feel there is no need to create a new field under the banner of ecosystem health because its content is already accommodated within ecology (and its extensions, such as stress ecology, conservation biology, ecological economics or ecological engineering).

In reply, one could argue that events have simply over-taken many of these concerns. The specification of indicators provides examples of quantitative ‘operational measures’ of ecosystem health. There is widespread recognition of ecosystem pathology not only among ecologists[15,24] but also among economists, microbiologists and those working in human health fields[25,26]. The cardinal objections that health is a property only of organisms and that measures of health are simple (because the properties of organisms are tightly regulated) do not bear up under close scrutiny. Health concepts have long been applied at the herd and population level, and extension to the ecosystem and landscape level[27,28] is another step in a natural progression. Although it is true that many properties of organisms are tightly regulated, this is only a matter of degree — some characteristics of organisms fluctuate widely over their life cycle. There is no denying that the domain of ecosystem health is large, but it breaks down into distinct challenges that provide opportunities for integrative research among the social, natural and health sciences.

Challenges for ecologists and evolutionary biologists

The primary challenge of this field is effective integration of ecology with the social and health sciences[29]. Ecosystem health assessments require analysis of linkages between human pressures on ecosystems and landscapes, altered ecosystem structure and function, alteration in ecosystem services, and societal response. Effective diagnosis requires exploring and identifying the most critical of these links.

Many questions remain:

• How is the human impact on ecosystems distinguished from natural perturbations, which may also cause dramatic changes?

• What are the possible effects of landscape configurations on the spread of certain diseases, particularly those associated with animal vectors (e.g. hantavirus and Lyme disease)?

• What landscape and human settlement patterns might mitigate the spread of such diseases?

• What are the strategies to keep systems from becoming pathological?

• For all of these issues, what is the role of adaptation within altered ecosystems?

These questions transcend specific disciplines and require an integrated, holistic approach[30,31]. With more concerted efforts to integrate the health sciences with those of the natural and social sciences, progress is expected in devising workable strategies for preventing deterioration in the life-support systems of Earth.

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References

1 Vitousek, P.M. et al. (1977) Human domination of earth’s ecosystems, Science, 277, 494–497

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43 Smith, B. et al. (1996) Ecosystem Health: Analysis and Assessment, University of Guelph


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