Assessing ecosystem health

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

Evaluating ecosystem health in relation to the ecological, economic and human health spheres requires integrating human values with biophysical processes, an integration that has been explicitly avoided by conventional science. The field is advancing with the articulation of the linkages between human activity, regional and global environmental change, reduction in ecological services and the consequences for human health, economic opportunity and human communities. Increasing our understanding of these interactions will involve more active collaboration between the ecological, social and health sciences. In this, ecologists will have substantive and catalytic roles.

D.J. Rapport is at the Faculty of Environmental Sciences, University of Guelph, Canada N1G 2W1 (drapport@envsci.uoguelph.ca) and at the Dept of Pharmacology and Toxicology, Faculty of Medicine and Dentistry, The University of Western Ontario, Canada N6A 5B7; R. Costanza is at the Center for Environmental Science, the Biology Dept and the Institute for Ecological Economics, University of Maryland, PO Box 38, Solomons, MD 20688, USA (costza.@cbl.umces.edu); A.J. McMichael is at the Dept of Epidemiology and Population Health, London School of Hygiene and Tropical Medicine, Keppel Street, London, UK WC1E 7HT (tony.mcmichael@lshtm.ac.uk).

There is now abundant evidence that many human-dominated ecosystems, including various biophysical systems at regional and global levels, have become highly stressed and dysfunctional[1]. The 'services' provided by these ecosystems are extremely important to human welfare[2–5]. As stressed ecosystems have become highly degraded[1,6–9], they have also become incapable of supplying services to the same level as in the past[5,10]. The capacity of the environment to sustain economic activity[4,10] and human health[11–15] 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[16]. 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)[17] is widely prevalent in both aquatic and terrestrial ecosystems[18]. 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 human-dominated ecosystems have become highly dysfunctional[1]. 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[19]. What is needed are methods for identifying dysfunction and evaluating causes and potential solutions.

Definitions of ecosystem health[20,21] have been closely allied with the concepts of stress ecology[19,22,23], which define health in terms of 'system organization, resilience and vigor, as well as the absence of signs of ecosystem distress[24]. 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[24]. Assessment of these properties in large-scale systems through specific indicators of resilience, organization and vigor has been attempted for the Chesapeake Bay[25] (USA) and other marine ecosystems[26], freshwater ecosystems[27], forested ecosystems[18], arctic ecosystems[28] and arid grasslands[29]. Boxes 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[30]. However, careful studies leave little doubt that degradation has occurred in many ecosystems, including forests[6], marine systems[7], agroecosystems[31,32] and freshwater[33]. Indeed,

Box 1. Indicators of ecosystem health

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

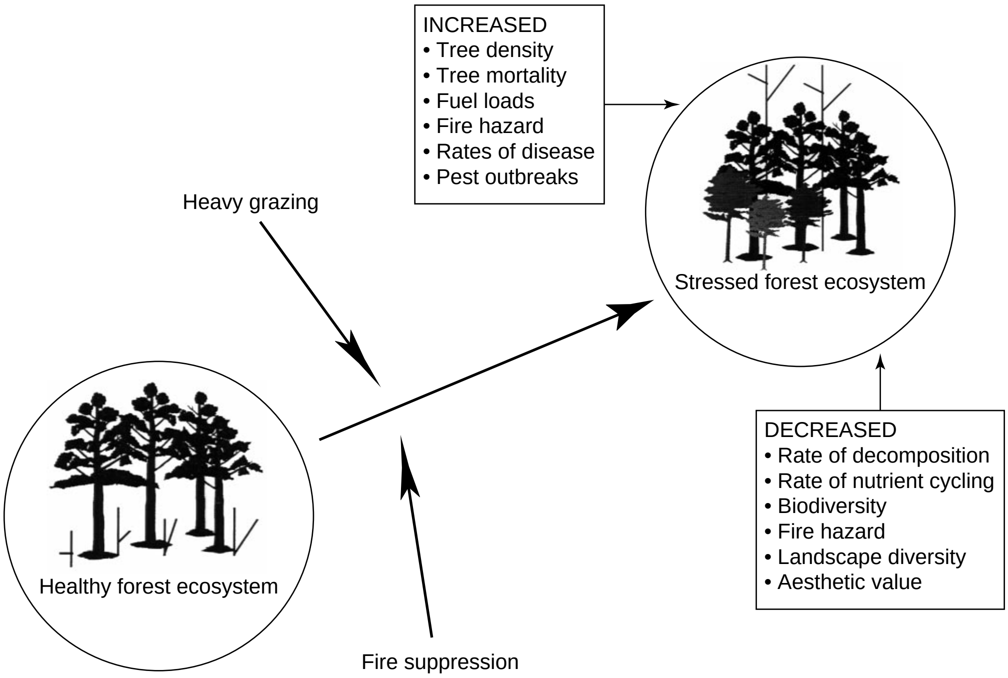
Vigor is measured in terms of 'activity, metabolism or primary productivity'[25]. An example of reduced vigor, from a study of the Great Lakes Basin (North America)[10], is the decline in the abundance of fish and infertility of agricultural soils within the basin (Box 3).

Organization can be assessed as the diversity and number of interactions between system components. An example, also from the Great Lakes, is reduced morphological and functional diversity of fish associations that occurs under multiple stresses (Box 3).

Resilience (counteractive capacity)[23], 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 Lower Great Lakes Basin[10] (Box 3).

  0169-5347/98/$19.00 PII: S0169-5347(98)01449-9

Box 2. Health of a Ponderosa pine ecosystem



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[18] (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[18] 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 fires. With fire suppression, the ecosystem displayed signs of EDS, including decreased productivity and increased mortality of Ponderosa pine, stagnated nutrient cycles, increased rates 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.

degradation is so large in some regions that whole ecosystems have become endangered[34]. These changes have led to a reduction in the flow of ecosystem services[4,5] (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-sized age classes and consequently caused an increase in the production of pulp and paper[10]. 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)[10]. The recognition of the value of ecosystem services depends largely on the extent of 'environmental literacy'[3]. With a high degree of literacy, most ecosystem functions would be perceived, directly or indirectly, to benefit humankind. However, from the public's perception[35], 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[4]. 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.

Human health: dependency on ecological support

An important effect of ecosystem degradation is an increased risk to human population health[11,13,14,36–39]. In addition to the familiar toxicological risks resulting from bioaccumulation of toxic substances (e.g. mercury, lead and organocarbons), 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[36] (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.

The life-supporting systems of the biosphere include marine and terrestrial food-producing systems, wetlands that maintain water quality, the ecological constraints on infectious disease agents and their vectors, and the buffering against natural disasters (floods, storms and landslides, etc.) provided by conserved forests and coastlines. If large-scale environmental changes occur, such as climate change, land degradation and biodiversity loss, then we must expect that the life-supporting capacity of the biosphere will diminish. For example, such changes will alter the geographical range of, and the pattern of human contact with, various infectious diseases. They will also affect the productivity of agroecosystems, 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 ways[40]. The vector-borne infection Lyme disease, which is spread by spirochete-infected Ixodes ticks, has increased over several decades in northeast USA and in parts of central–northern Europe. The ticks, which acquire the infection from rodents (*Peromyscus leucopus*), spend part of their life-cycle on deer (*Odocoileus virginianus*). The elimination of natural predators and recent reforestation of abandoned farmland (compounded by sylvan suburban living) has caused an increase in the USA deer population this century and, consequently, there is a much increased potential for human exposure to infected ticks[39].

The El Niño event of the early 1990s, 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 disease[41], 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 humans and contaminated drinking water. Recent evidence indicates that aquatic ecosystems provide a natural reservoir for the bacterium, where it remains dormant in phytoplankton and zooplankton[38]. The environmental conditions that cause algal blooms (such as climate-induced warming of waterways and their eutrophication by agricultural and domestic nitrate and phosphate runoff) and the subsequent proliferation of zooplankton might therefore act to increase dissemination of cholera into human populations.

We have only recently begun 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

Box 3. Assessment of ecosystem health in the Central Rio Grande Valley and the Great Lakes Basin

The Central Rio Grande Valley in New Mexico represents a practical application of measuring indicators of ecosystem health at different spatial scales. The region was targeted for ecosystem health assessment because of rapid changes resulting from the high level of human activity concentrated in the river valley. The irrigated valley produces many of the cash crops valuable to the USA's economy, and an estimated two million people depend directly on the basin, which is considered to be North America's largest intensively engineered flood-plain landscape[29]. Important indicators of ecosystem health in this landscape include biodiversity and water quality. Symptoms of degrading ecosystem conditions include the prevalence of exotic species and disease, water contamination and loss of riparian forests. The spread of exotic species affects the productivity of farm fields by reducing the production potential of the native grass strips between the river levees. Increased disease prevalence is the indirect result of reduced biodiversity, marked by the loss of gallery forests (which have been replaced by cottonwoods). These trees become focal points for roosting birds, which are vectors of the parasitic plant, mistletoe (*Phoradendron tomentosm*). Reduced water quality is the result of the leaching of nitrates and coliform bacteria from manure, which are discharged through runoff. The contaminated water, together with the loss of riparian forests and their inherent filtration capacity, has resulted in contaminated runoff reaching the water system unabated. Another contributing factor to reduced water quality is the occurrence of unregulated human settlements ('colonias'), which discharge raw sewage directly into irrigation ditches. All of these anthropogenic stresses are causing extreme ecological degradation to the Central Rio Grande ecosystem.

A somewhat different pattern of pressures has impacted the Laurentian Lower Great Lakes Basin (Lake Ontario and Lake Erie, North America). Before the early 19th century, which marked the beginning of European settlement, the region was characterized by a high abundance and diversity of forests, fish and mammals[10]. With the establishment of intensive agriculture, commercial fishery and forestry operations, and building of canals, the biophysical character of the basin changed dramatically. The three primary attributes of ecosystem health were adversely affected: reduced productivity was evident from the decline in fish abundance and infertility of agricultural soils; lowered resilience became apparent after many decades of overfishing and other stresses (such as the introduction of exotic species, leading to the local extinction of native fish species); changes in organization (community structure) became evident with a shift in dominance from highly organized nearshore benthic-fish associations to the relatively less organized offshore pelagic associations.

The loss of resilience resulted in widespread extinctions of native fish species and a flip to eutrophic conditions, characterized by periodic anoxia over large areas of bottom waters of the central basin of Lake Erie, and radical shifts in the structure of fish communities from once dominant littoral and demersal terminal-predators and benthic feeders (consisting of more specialized stocks and high species diversity) to offshore pelagic associations composed of exotic species. Additional indicators of decline in the health of the Laurentian Lower Great Lakes Basin include an associated loss of ecosystem services, such as the decline in water quality, the loss of edible fish (owing to the accumulation of toxic substances, which have resulted in health advisories suggesting limits to consumption), loss of the once thriving commercial fishery, and virtual depletion of the commercial timber resources of the basin.

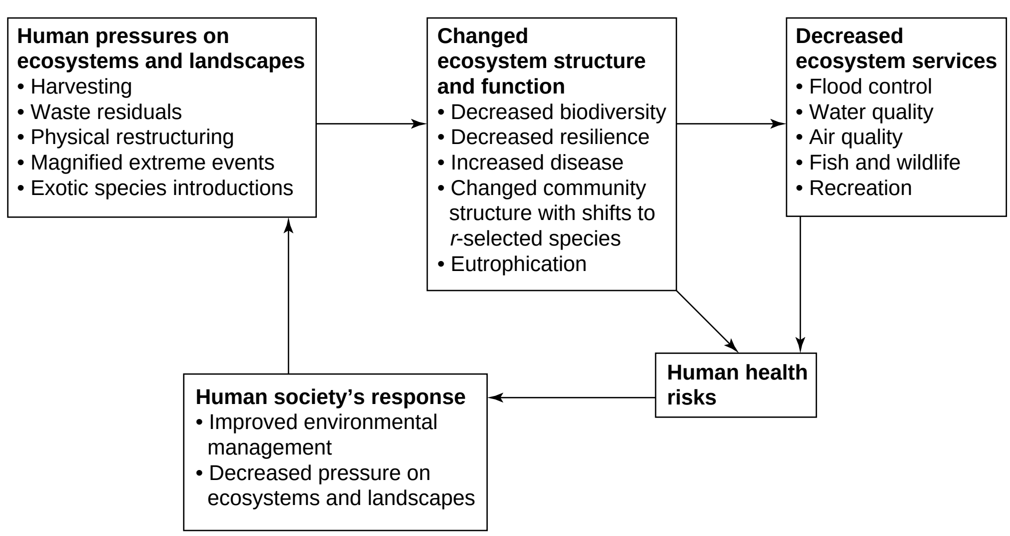


Fig. 1. Linkages between pressures from human activity, ecosystem change and degradation of ecosystem and human health.

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

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

[a]Modified from Ref. 36.

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[24]. 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[42]. 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[42–44].

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 collective efforts of the Governments of Canada and the USA to assess the state of ecosystem health in the Great Lakes[45]. 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 risks 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, understorey 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 on the human communities for whom the forests are 'home'. 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 their 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 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 overtaken many of these concerns. The specification of indicators provides examples of quantitative 'operational measures' of ecosystem health[25]. There is widespread recognition of ecosystem pathology not only among ecologists[2,3,5], but also among economists, microbiologists and those working in human health fields[4,11,49]. 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[44,50] 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[39]. 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[30]?
• To what extent are ecosystem services maintained despite altered ecological communities?
• 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[51,52]. 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.

Acknowledgements

The authors acknowledge the support of the Tri-Council (social, natural and medical research councils of Canada) and the Richard Ivey Foundation. Thanks also to Ellen Woodley for reviewing and editing the article and to anonymous reviewers for their helpful comments.

References

1 Vitousek, P.M. *et al.* (1997) **Human domination of earth's ecosystems,** *Science* 277, 494–499
2 Cairns, J., Jr (1997) **Protecting the delivery of ecosystem services,** *Ecosyst. Health* 3, 185–194
3 Cairns, J., Jr and Pratt, J.R. (1995) **The relationship between ecosystem health and delivery of ecosystem services,** in *Evaluating and Monitoring the Health of Large-Scale Ecosystems* (Rapport, D.J., Gaudet, C. and Calow, P., eds), pp. 63–76, Springer-Verlag
4 Costanza, R. *et al.* (1997) **The value of the world's ecosystem services and natural capital,** *Nature* 387, 253–260
5 Daily, G. (1997) *Nature's Services: Societal Dependence on Natural Ecosystems*, Island Press
6 Noble, L.R. and Dirzo, R. (1997) **Forests as human-dominated ecosystems,** *Science* 277, 522–525
7 Botsford, L.W., Castilla, J.C. and Peterson, C.H. (1997) **The management of fisheries and marine ecosystems,** *Science* 277, 509–515
8 Hildén, M. and Rapport, D.J. (1993) **Four centuries of cumulative impacts on a Finnish river and its estuary: an ecosystem health approach,** *J. Aquat. Ecosyst. Health* 2, 261–275
9 Hagler, M. (1995) **Deforestation of the deep: fishing and the state of the oceans,** *Ecologist* 25, 74–79
10 Regier, H.A. and Baskerville, G.L. (1986) **Sustainable redevelopment of regional ecosystems degraded by exploitive development,** in *Sustainable Development of the Biosphere* (Clark, W.C. and Munn, R.E., eds), pp. 75–103, Cambridge University Press
11 McMichael, A.J. (1993) **Global environmental change and human population health: a conceptual and scientific challenge for epidemiology,** *Int. J. Epidemiol.* 22, 1–8
12 McMichael, A.J. (1993) *Planetary Overload: Global Environmental Change and the Health of the Human Species*, Cambridge University Press
13 McMichael, A.J. (1997) **Global environmental change and human health: impact assessment, population vulnerability, research priorities,** *Ecosyst. Health* 3, 200–210
14 Patz, J.A. *et al.* (1996) **Global climate change and emerging infectious diseases,** *J. Am. Med. Assoc.* 275, 217–223
15 Epstein, P.R. (1995) **Emerging diseases and ecosystem instabilities: new threats to public health,** *Am. J. Pub. Health* 168–172
16 Rio Declaration on Environment and Development (1992) *The Earth Summit: the United Nations Conference on Environment and Development* (Johnson, S., ed.), Graham and Troutman/ Martinus Nijhoff, London
17 Rapport, D.J., Regier, H.A. and Hutchinson, T.C. (1985) **Ecosystem behavior under stress,** *Am. Nat.* 125, 617–640
18 Yazvenko, S.B. and Rapport, D.J. (1997) **The history of Ponderosa pine pathology: implications for management,** *J. For.* 95, 16–20
19 Barrett, G.W. and Rosenberg, R. (1981) *Stress Effects on Natural Ecosystems*, John Wiley & Sons
20 Schaeffer, D.J., Henricks, E.E. and Kerster, H.W. (1988) **Ecosystem health: 1. Measuring ecosystem health,** *Environ. Manage.* 12, 445–455
21 Haskell, B.D., Norton, B.G. and Costanza, R. (1992) **What is ecosystem health and why should we worry about it?** in *Ecosystem Health: New Goals for Environmental Management* (Costanza, R., Norton, B.G. and Haskell, B.D., eds), pp. 3–19, Island Press
22 Odum, E. (1985) **Trends expected in stressed ecosystems,** *BioScience* 35, 419–422
23 Rapport, D.J. (1989) **What constitutes ecosystem health?** *Perspect. Biol. Med.* 33, 120–132
24 Costanza, R. (1992) **Toward an operational definition of ecosystem health,** in *Ecosystem Health: New Goals for Environmental Management* (Costanza, R., Norton, B.G. and Haskell, B.D., eds), pp. 239–256, Island Press

25 Mageau, M.T., Costanza, R. and Ulanowicz, R.E. (1995) **The development and initial testing of a quantitative assessment of ecosystem health,** *Ecosyst. Health* 1, 201–213

26 Rapport, D.J. (1989) **Symptoms of pathology in the Gulf of Bothnia (Baltic Sea): ecosystem response to stress from human activity,** *Biol. J. Linn. Soc.* 37, 33–49

27 Wichert, G. and Rapport, D.J. (1998) **Fish community structure as a measure of degradation and rehabilitation of riparian systems in an agricultural drainage basin,** *Environ. Manage.* 22, 425–443

28 Rapport, D.J., Hildén, M. and Roots, E.F. (1997) **Transformations in arctic ecosystems under stress,** in *Disturbance and Recovery in Arctic Lands: an Ecological Perspective* (Crawford, R.M.M., ed.), pp. 73–90, Kluwer

29 Whitford, W.G., Rapport, D.J. and Groothousen, R.M. (1996) **The Central Rio Grande Valley,** *GIS World* 9, 60–62

30 Sprugel, D.G. (1991) **Disturbance, equilibrium and environmental variability: what is 'natural' vegetation in a changing environment?** *Biol. Conserv.* 58, 1–18

31 Pimentel, D. *et al.* (1995) **Environmental and economic costs of soil erosion and conservation benefits,** *Science* 267, 1117–1123

32 Oldeman, K., van Engelen, V. and Pulles, J. (1990) **The extent of human-induced soil degradation,** in *World Map of the Status of Human-Induced Soil Degradation: an Explanatory Note* (Rev. 2nd edn) (Oldeman, L.R., Hakkeling, R.T.R. and Sombroek, W.G., eds), Annex 5, International Soil Reference and Information Centre, Wageningen

33 Postel, S. and Carpenter, S. (1997) **Freshwater ecosystems services,** in *Natures Services: Societal Dependence on Natural Ecosystems* (Daily, G., ed.), pp. 195–214, Island Press

34 Noss, R.F. (1996) **Ecosystems as conservation targets,** *Trends. Ecol. Evol.* 11, 351

35 Bormann, F.H. (1996) **Ecology: a personal history,** *Annu. Rev. Energ. Environ.* 21, 1–29

36 McMichael, A.J. and Haines, A. (1997) **Global climate change: the potential effects on health,** *Br. Med. J.* 315, 805–808

37 Brown, N. (1998) **Out of control: fires and forestry in Indonesia,** *Trends Ecol. Evol.* 13, 41

38 Colwell, R. (1996) **Global climate and infectious disease: the cholera paradigm,** *Science* 274, 2025–2031

39 Wilson, M.E. (1995) **The emergence of new diseases: learning from the past and preparing for the future,** in *The Diagnostic Challenge: Knowledge for Health* (Fischer, E.P. and Klose, S., eds), pp. 11–69, Piper

40 Dobson, A. and Carper, R. (1993) **Health and climate change,** *Biodivers. Lancet* 342, 1096–1099

41 Duchin, J.S. *et al.* (1994) **Hantavirus pulmonary syndrome: a clinical description of 17 patients with a newly recognized disease,** *N. Engl. J. Med.* 330, 949–955

42 Ribble, C. *et al.* (1997) **Ecosystem health as a clinical rotation for senior students in Canadian veterinary schools,** *Can. Vet. J.* 38, 485–490

43 Smit, B. *et al.* (1998) *Agroecosystem Health: Analysis and Assessment*, University of Guelph

44 Rapport, D.J. *et al.*, eds (1998) *Ecosystem Health*, Blackwell

45 Shear, H. (1996) **The development and use of indicators to assess the state of ecosystem health in the Great Lakes,** *Ecosyst. Health* 2, 241–258

46 Calow, P. (1992) **Can ecosystems be healthy? Critical considerations of concepts,** *J. Aquat. Ecosyst. Health* 1, 1–5

47 Suter, G.W. (1993) **A critique of ecosystem health concepts and indexes,** *Environ. Toxicol. Chem.* 12, 1533–1539

48 Wicklum, D. and Davies, R.W. (1995) **Ecosystem health and integrity?** *Can. J. Bot.* 73, 997–1000

49 Arrow, K. *et al.* (1995) **Economic growth, carrying capacity, and the environment,** *Science* 268, 520–521

50 Rapport, D.J., Gaudet, C. and Calow, P., eds (1995) *Evaluating and Monitoring the Health of Large Scale Ecosystems*, Heidelberg

51 Kevan, P.G., Greco, C.F. and Belaoussoff, S. (1997) **Log-normality of biodiversity and abundance in diagnosis and measuring of ecosystem health: pesticide stress on pollinators on blueberry heaths,** *J. Appl. Ecol.* 34, 1122–1136

52 Wilson, E.O. (1998) *Consilience: the Unity of Knowledge*, Knoff