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OVERVIEW ARTICLE

# Sustainability science: an ecohealth perspective

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**Abstract** Sustainability science is emerging as a transdisciplinary effort to come to grips with the much-needed symbiosis between human activity and the environment. While there is recognition that conventional economic growth must yield to policies that foster sustainable development, this has not yet occurred on any broad scale. Rather, there is clear evidence that the Earth's ecosystems and landscapes continue to degrade as a consequence of the cumulative impact of human activities. Taking an ecohealth approach to sustainability science provides a unique perspective on both the goals and the means to achieve sustainability. The goals should be the restoration of full functionality to the Earth's ecosystems and landscapes, as measured by the key indicators of health: resilience, organization, vitality (productivity), and the absence of ecosystem distress syndrome. The means should be the coordinated (spatially and temporally) efforts to modify human behaviors to reduce cumulative stress impacts. Achieving ecosystem health should become the cornerstone of sustainability policy—for healthy ecosystems are the essential precondition for achieving sustainable livelihoods, human health, and many other societal objectives, as reflected in the Millennium Development Goals.

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## The nature of sustainability science

"Sustainability science" is, at root, a transdisciplinary effort to come to grips with one of the most perplexing issues of our time: how to achieve a symbiotic relationship between biological and social–cultural systems so that future options are not foreclosed. It is not a "science" by any usual definition—that is, it is not yet a set of principles by which knowledge of sustainability may be systematically built. Rather, it consists of a plethora of ideas and perspectives, sometimes conflicting, by which one might hope to achieve a viable future for humankind. All approaches recognize, in one way or another, that "our common future" depends critically upon preserving the life-giving functions of the Earth's ecosystems, landscapes, and biosphere. To achieve this requires the deepening of our understanding of the linkages between the "global system" (the planetary base for human survival), the "social system" (the political, economic, industrial, and other human-devised structures that provide the societal basis of human existence), and the "human system" (the sum total of all factors impacting the health of humans) (Komiyama and Takeuchi 2006).

While, at present, there is no generally accepted methodology for obtaining the much-needed symbiosis between nature and culture, it is recognized that knowledge from many disciplines has a critical role to play in working towards this goal. The key objective is one of reconciling society's development goals and natural system constraints (Clark and Dickson 2003; Kates et al. 2001). In this, it is critical to understand the dynamics by which human activities shape and influence the state of the environment and the dynamics by which changes in the state of the environment impact on human well-being (Rapport and Singh 2006).

The wake-up call for sustainability was sparked several decades ago by the report to the Club of Rome on ''The limits to growth.'' This study, although built upon very simplified assumptions, showed that unbridled conventional economic growth is unsustainable. Clearly, there are limits to growth of the type that results in the depletion of non-renewable resources, for, ultimately, there will be ''overshoot and collapse'' of population and the economic base (Meadows et al. 1972). Technological optimists have rejected this thesis, claiming that, as the depletion of one resource is approached, economic incentives will result in new technologies such that the depleted resource is no longer essential for human development. This may be true to some degree; for example, the desalinization of sea water has augmented or substituted for the limited supplies of fresh water in some special cases, but this solution cannot be universally adopted, owing to practical and financial constraints. However, the technological optimists have neglected a more fundamental constraint, namely, requirements for ecological functions. As many global and sub-global models have subsequently shown, unabated conventional economic development has already resulted in the degradation of ecological systems on a large scale. The report of the World Commission on Environment and Development warned that human activities must be tempered if development is to be ecologically supportable (WCED 1987). They advocated a policy of ''sustainable development,'' that is, ''development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs'' (WCED, p. 8). The WCED affirms the notion of limits to growth, although not in absolute terms, but, rather, limits set by the state of technology, social organization, and the capacity of the biosphere to ''absorb the effects of human activities'' (WCED, p. 8).

Although several decades have passed since these landmark studies, there is scant evidence that the fundamental principles of sustainability have been implemented by the world community to any significant degree. Assessments of the state of global and sub-global environments (e.g., the GEO 3 Report, the Millennium Assessment, etc.) suggest that the viability of many of the Earth's ecosystems is already in decline (UNEP 2002; Hassan et al. 2005). At the same time, there has been a decline in the diversity of cultural systems, as evidenced by the continued loss of the world's languages and traditional environmental knowledge (Maffi 2001).

In view of these trends, there is a pressing need to come to grips afresh with the nature of sustainability and to seek ways and means to harmonize human goals and aspirations within ecosystem constraints. Indeed, a variety of new cross-disciplinary fields have emerged over the past several decades that collectively provide a kaleidoscope of approaches to sustainability. These ''hybrid fields'' include environmental law, ecological economics, ecological engineering, environmental health, conservation biology, and so on. Ecosystem health is a relative newcomer to this family of cross-disciplinary approaches to questions of the sustainability of nature and culture.

## Ecosystem health: an evolving transdisciplinary science and practice

Healthy ecosystems and landscapes are those that, on some regional scale, maintain their full functions, unimpaired, while, at the same time, making it possible for human settlement. Ecosystem health is the study of the circumstances that enable ecosystems to maintain their full functionality while providing sustainable livelihoods and conditions that favor cultural well-being and public health. It seeks to identify key indicators of health at the ecosystem scale, taking the perspective that humans are part of, and not apart from, the system. Thus, the indicators are not only ecological in nature, but also involve social dimensions, including public health, cultural practice, sustainable livelihoods, governance, etc. Its focus is not only on measuring the health state of ecosystems and landscapes, but also on the determinants of health—that is, the relationship of human activity to transformations in ecosystem and landscapes. Its perspective differs significantly from prevailing economic and engineering approaches. The concept of ''health'' or ''well functioning'' of ecosystems is often ignored by the prevailing engineering and economic approaches to environmental management, in which efficiency and monetary value are the key measures of success. From the ecosystem health perspective, the maintenance of the health of ecosystems, so that they maintain their full potential to sustain life itself, is the primary focus.

The field of ecosystem health integrates many specialized areas of knowledge drawn from the social, natural, and health sciences. Landscape ecology, applied ecology, public health, veterinary and human medicine, cultural anthropology, and economics, to name but a few, all have made significant contributions to the development of the field of ecosystem health (Rapport et al. 2003).

In a nutshell, healthy ecosystems are an essential condition of healthy people, healthy communities, and sustainable livelihoods. In many countries of the world, great strides have taken place in the economic realm, and also, in improving life expectancies. However, such gains are not sustainable if, as is the case in many situations, ecosystem functions are, at the same time, being compromised. This basic fact has been recognized for many centuries, if not for millennia. In ancient Greece, the great philosopher Plato noted marked deterioration in waters which had sewage inflow. By the eighteenth century, the citizens of Paris and London, while well aware that urban development had many benefits in terms of material well-being, were also aware that industrial processes and inattention to the needs to assimilate urban waste had resulted in grave damage to their rivers—which, as a source of drinking water, was, in fact, the life-line of the city. In recent times, the great American naturalist, Aldo Leopold, noticed a number of tell-tale signs of what he termed ''land sickness'' in his native Wisconsin farm and woodlands. Agricultural development had clearly resulted in compromising the viability of agro- and forest ecosystems. Leopold pointed to soil erosion, nutrient depletion, loss of native species, increases in invasive species, increase in plant and animal pathogens, etc. as the key indicators of ''land sickness'' (Leopold 1941). Leopold suggested that the key to the sustainability of human settlement and agricultural practice was to maintain the ''health'' of the land (Leopold et al. 1999).

In the late 1970s, a collaboration among a vascular surgeon, Dr. Chris Thorpe, a fisheries biologist/ecologist, Dr. Henry Regier, and myself established the foundations for the integrative field of ecosystem health (Rapport et al. 1979). At the time, we were unaware of the pioneering work of Leopold, who had come to similar conclusions decades earlier; namely, that the Earth's ecosystems were becoming highly compromised as a result of anthropogenic stress and that one could establish a set of key indicators that could be used to assess the health of ecosystems. Unfortunately, most of Leopold's writings on the topic were unknown in the 1970s and remained unpublished until 1999, with the exception of his somewhat obscure short essay on land sickness (Leopold 1941).

My collaboration with Thorpe and Regier resulted in the publication of a short essay entitled ''Ecosystem medicine'' (Rapport et al. 1979), in which we suggested that diagnostic protocols used in Western medicine might have some application to the systematic evaluation of the conditions of ecosystems. To do this, we drew from the common medical practice of the identification of ''vital signs'' by which to assess health, and sought an appropriate set of vital signs that might have relevance at the ecosystem level. We suggested that, among the potential vital signs of ecosystems, these were nutrient and energy flows, soil nutrients, biodiversity, and the capacity of ecosystems to rebound from natural perturbations such as floods, fire, etc. Establishing quantitative baselines for particular ecosystems for these and other vital signs would enable one to identify situations in which ecosystem functions and structure were out of ''normal bounds'' and, thus, had become compromised.

The extension of ''health assessments'' from the individual to the ecosystem level does not imply, however, that ecosystems are organisms or even ''super-organisms'' (Rapport et al. 1985). Clearly, ecosystems are organized along very different principles, i.e., they do not possess the equivalent of a ''central nervous system'' and so forth, nor are they subject to ''natural selection'' in the manner of individual organisms. Further, using concepts of health at the ecosystem level does not require making the analogy between ecosystems and organisms. All that is required is the recognition that ''health'' is a fundamental property of life systems at all levels of organization, from cells to the biosphere. At each level, health can be compromised (impaired) under certain conditions, and complex systems at all levels in the biological hierarchy can break down.

The focus of ecosystem health practice is twofold: (1) to ''diagnose,'' through indicators, situations in which ecosystem function (and structure) has become compromised, owing to anthropogenic stress or other causes; (2) to devise diagnostic protocols to assess the causes of dysfunction and propose interventions that may restore ecosystem health. Some of the most successful interventions are often regulating human behaviors to reduce stress on ecosystems. However, in seriously damaged ecosystems, that alone may be insufficient and active interventions may be needed; for example, in the restoration of streams by restoring riparian vegetation and stream bank configurations. It is also important to develop a ''preventive'' practice of ecosystem health, one which focuses on reducing the risks of compromising ecosystem function.

In the assessment of the health of ecosystems, two sets of measures are generally employed. One set focuses on confirming ecosystem pathology in systems under considerable pressure from anthropogenic stress, which involves identifying indicators of dysfunctional ecosystems (Rapport 1989a). The other set focuses on ecosystem health—that is, identifying attributes of fully functional ecosystems (Rapport 1989b).

## Indicators of ecosystem pathology: the ecosystem distress syndrome

Although ecosystems differ markedly from one another, due to many factors (including climate, hydrology, physiography, biotic associations, etc.), and although each ecosystem has a unique history with respect to exposure and intensity of anthropogenic stress, one can observe highly similar responses once the ecosystem breakdown process begins. The ''ecosystem distress syndrome'' (EDS) characterizes the response of many different ecosystems to various sources of anthropogenic stress (Rapport et al. 1985). Signs of EDS are: loss of biodiversity (to which we may also add, in many cases, cultural diversity; see Maffi 2001), reduced productivity (or system ''vitality''), leaching of soil nutrients, shifts in community composition to favor smaller life forms, reduced symbiotic relationships amongst biota, increased success of invasive species, loss of endemic species, increased presence of contaminants (particularly toxic substances that bio-accumulate in the food web), increased disease prevalence in various component species (including *Homo sapiens*), reduced efficiencies in nutrient transport, and reduced productivity/respiration ratios (Rapport et al. 1985; Rapport and Whitford 1999).

Such changes generally result in the loss of a number of so-called ''ecosystem services,'' an economic concept referring to functions performed ''free of charge'' by ecosystems that are of direct benefit to humans. In reality, all functions of ecosystems are vital to maintaining life systems, but some are recognized as more obviously of direct benefit to humankind, such as the provisioning of food and water (Costanza et al. 1997). For example, forest ecosystems provide many services, including the filtration of water (clean water), wood, food supplies from the harvest of forest game, stabilizing land forms (thus, protecting against mud slides), and providing recreational opportunities (such as bird watching, etc.). When forest ecosystems are compromised, there are significant losses in such ecosystem services, including, generally, a decrease in water quality and quantity, loss of fish habitat (in lakes, rivers, coastal areas within the watershed), loss of stability of land forms (resulting in increased risk of mud slides during heavy rains), loss of subsistence (e.g., hunting of game found in mature forests), etc. In short, anthropogenic stress on ecosystems, evidenced by the appearance of EDS, results in the reduction of ecosystem services, and, thus, of human well-being. As humans are part of the ecosystem, the loss of ecosystem services may serve as a ''blanket indicator'' of the deterioration in ecosystem health (Rapport 1995).

Another example of this chain of events, anthropogenic stress—the appearance of ecosystem distress function—and the loss of ecosystem services can be seen in the history of the Laurentian Lower Great Lakes (Lake Erie and Lake Ontario, USA). In this situation, the lakes have been subject to the cumulative impact of a number of sources of anthropogenic stress for nearly two centuries (since European settlement). These stresses include the over-harvesting of fish, nutrient loading, the introduction of contaminants, many of which are toxic to living organisms, the introduction of exotic species, physical restructuring of shorelines, wetland drainage (for agriculture or urban development), etc. As a consequence, signs of EDS begin to appear by the early 1950s. These included reductions in species diversity (particularly in fish communities in harbors and bays), shifts in species dominance to favor smaller life forms (e.g., in fish communities, the shift from dominance by large benthic fish to small pelagic fish), increases in the concentration of nutrients (particularly phosphorus), increases in invasive species (e.g., the sea lamprey, smelt, alewife), increased disease prevalence (manifest in physiological abnormalities in fish and wildlife), increase in water-borne pathogens, and increase in the circulation of toxic substances within the water column and the biota. Such changes sharply reduced a number of ecosystem services. For example, there was a marked loss of most commercial fisheries (as a result of over-harvesting and other stresses), a loss of biodiversity, particularly within the near-shore fish community, a loss in the availability of edible fish, owing to their high levels of substances toxic to humans, loss of recreational opportunity (e.g., beach closures owing to public health concerns about human pathogens, e.g., fecal coliform bacteria), etc. (Bertram et al 2003).

## Indicators of healthy ecosystems

It is often relatively easy to identify the features of compromised ecosystems, but it is more difficult to recognize the key features of healthy (fully functional) ecosystems. There is a parallel in human medicine: it is generally easy to know when one is sick, but difficult to identify the indicators of health. For ecosystems, four groups of indicators are generally used in making health assessments. One of these is the degree to which signs of ecosystem distress are absent. This is, in essence, the absence of signs of sickness. On the positive side, the presence of the following attributes provides indicators of health: (1) resilience, (2) organization, and (3) ‘‘vitality’’ (productivity) (Haskell et al. 1992; Rapport et al. 1998).

Resilience, or ‘‘counteractive capacity,’’ is a measure of the capability of ecosystems to recover from disturbance, i.e., recover from natural perturbations. In healthy ecosystems, recovery from fire, floods, wind, and hail storms, etc. is part of an adaptive cycle: forests recover from disturbances such as fire or wind storms; streams recover from floods and spring run-off; grasslands recover from long periods of drought; and so forth. These recovery patterns are normal for healthy ecosystems. However, if the health of the ecosystem has become compromised owing to anthropogenic stress, recovery from natural perturbations will, in many cases, be slower and less complete. This hypothesis was tested in desert grassland ecosystems using a stress gradient created by cattle grazing patterns. Assessing the density and composition of key perennial grasses before and after a prolonged drought showed that recovery (resilience) was considerably higher in the less stressed part of the gradient than in the heavily stressed areas (Whitford et al. 1999).

Organization can be assessed in terms of the interactions between biota and their environment. In healthy ecosystems, there are many specialized interactions that link species together (such as predator–prey relationships, symbiotic relationships, parasitic relationships, etc.). Different taxa within communities (avian species for example) often apportion the available habitat in complex temporal and spatial ways that constitute an integrated structure. Again, to take the example of the history of the Laurentian Great Lakes Basin, anthropogenic stress has resulted in the loss of organization. This is evidenced by a shift from the highly organized near-shore benthic fish associations, which dominated the lake and served as ‘‘organizing centers’’ for lake processes, to offshore pelagic fish communities, which are relatively less organized (Rapport 1983). This dramatic transformation of the fish community in the Laurentian Lower Great Lakes Basin was not a temporary shift, but, rather, constituted a long-term change in the fundamental structure of the system (Rapport 1983).

‘‘Vitality’’ (or vigor) can be measured in terms of ‘‘activity, metabolism, or primary productivity’’ (Mageau et al. 1995). In many areas of the world, the productivity of ecosystems has been severely compromised as a result of a variety of stresses, ranging from the pollution of air and water (acid precipitation on land for example), over-harvesting (the collapse of the North Western Atlantic cod fishery for example), overgrazing (the degradation of the Mongolian grasslands, particularly Inner Mongolia), etc. Indeed, in some cases, highly productive ecosystems have all but disappeared (e.g., the Aral Sea, the Mesopotamian wetlands), and large arid grasslands once supporting a large and productive grazing population (bison, buffalo) have today become virtual deserts with moving sand dunes (Whitford 2002).

To this point, our examples of what are healthy ecosystems have been drawn largely from ecological perspectives. However, as humans are integral to the composition of ecosystems, it is also necessary to approach the question of evaluating the health of ecosystems from social, cultural, human health, and governance perspectives. Using the concept of resilience, for example, one might examine livelihoods in particular regions and how well they are able to buffer changes in economic conditions within a particular ecosystem or landscape. Similarly, one might look at the resilience of cultural traditions, perhaps in terms of the effectiveness of transmission of traditional knowledge from one generation to the next (Maffi 2001). The human health dimension of ecosystem health could be examined in terms of the capacity of people to cope with endemic disease risks, such as dengue fever and malaria in tropical countries, and in terms of nutritional status (McMichael 1993, 1997). Governance issues are also critical to the health of ecosystems (Ullsten 2003). Moving towards sustainability requires that communities which experience the impacts of human activities have a voice in determining what kinds of activities are acceptable. This is often not the case, particularly within the ever more ‘‘global economy.’’ In the mining and forestry sectors, as well as in water allocations, too often, decisions are taken by interest groups outside the community that ultimately bears the consequences in terms of environmental degradation.

## Anthropogenic stress on ecosystems and consequences for human well-being

Collectively, it is human activity—the complex interaction of population, technology, and human behavior—that has resulted in anthropogenic stress on most of the world’s major ecosystems. And while humans also have the ability to maintain and restore the health of ecosystems, on balance, degradation has far outpaced maintenance and restoration. Our ‘‘human-dominated’’ ecosystems (Vitousek et al. 1997) are, indeed, out of balance, and the result is seen in the increasing disappearance of natural areas and dysfunction within our landscapes and ecologies (Foley et al. 2005). The generation of waste residuals, over-harvesting of renewable resources, physical restructuring of the landscape, introduction of exotic species, and, most recently, the destabilization of the global climate through the release of greenhouse gases, also contribute individually and collectively to deteriorating the health of our regional and global ecosystems.

The loss of ecosystem health often entails increased vulnerabilities for human health, since degraded ecosystems often enhance the possibilities for the transmission of vector-borne and water-borne diseases (Epstein and Rapport 1996). Ecological imbalances may also give rise to the emergence of new pathogens or the resurgence of old ones (e.g., Lyme Disease, SARS, Hanta Virus, highly pathogenic Avian Influenza, pathogenic forms of *E. coli*, etc.) (Levins et al. 1994; McMichael 1997). While it has long been known that polluted environments are responsible for compromising human health, new contaminants, particularly persistent organic pollutants, are adding new and more insidious risks to human well-being (Rapport and Mergler 2004).

## An ecohealth perspective on sustainability science

An ecohealth perspective on sustainability science helps to focus on the critical issue of ''what it is that is to be sustained.'' Few scientists today would argue that conventional economic growth is compatible with the long-term sustainability of life systems. Yet, much economic activity and government policy is still predicated on that very assumption. Further, there is no general agreement amongst scientists and society as to the goals of sustainability. From an ecohealth perspective, the bottom line for achieving ''sustainability'' is maintaining or restoring the health of the Earth's ecosystems and landscapes (Rapport et al. 1998, 2003). To achieve this requires not only regaining the ecological attributes characteristic of well-functioning ecosystems and landscapes, but also achieving sustainable human livelihoods, human and animal health, and sustainable cultural traditions. All of this is the essence of a symbiotic relation of humans within ''nature.'' The goal of sustainability, thus, should be that cultural and ecological systems maintain their full functionality—not only for the benefit of present generations, but also for future generations; not only for the benefit of the human component (that is, the maintenance of ecosystem services), but for the benefit of all species.

As to the question of how to achieve this, an ecohealth perspective may offer some tentative guidelines. It is known, for example, that most ecosystems are damaged as a result of cumulative stress from human activities, and that the early warning signs of ecosystem degradation may be seen in a variety of indicators, such as the loss of the most sensitive species, the loss of cultural practices, increased human health vulnerabilities, loss or reduction in livelihoods, etc. These early warning signs should provide a strong signal for exercising the ''precautionary principle,'' which, in a nutshell, states ''play safe rather than sorry'' (Cooney and Dickson 2005). If, for example, it is known that nutrient loading from agricultural runoff can potentially seriously damage fisheries in coastal and inland waters, the precautionary principle would argue that one should limit agricultural practices that result in this source of potential damage to receiving ecosystems.

An ecohealth approach also requires recognition that ecosystems and landscapes are increasingly human-dominated and, thus, are heavily influenced by the constellation of human activities. While human activities can both enhance and degrade ecosystems (Rapport and Singh 2006), it the degradation aspect that most generally prevails. Thus, the remedy lies not so much in ''fixing the system'' as it does in changing human behaviors. Further, to effectively implement an ecosystem health approach, it is essential to develop a collaborative process amongst the various stakeholders. One of the key barriers to restoring the health of ecosystems has been fragmentation and the lack of coordination among the myriad of agencies and other parties involved. This is well illustrated in the failure of US agencies to restore health to coastal marine ecosystems (Crowder et al. 2006).

Given the overlap in multiple jurisdictions with respect to particular ecosystems and landscapes, and, consequently, the carving up of responsibilities amongst many agencies, it is no wonder that restoring the health of damaged ecosystems becomes, in practice, a bureaucratic nightmare. One way to overcome these obstacles is to seek ecosystem-based environmental accords, agreements, declarations, etc. that have the goal of the restoration of the health of regional ecosystems. For example, the Tulum Agreement brings together four countries of Mesoamerica for the common purpose of restoring the health of the Mesoamerican Coral Reef (Gawler et al. 2000).

One could readily argue that healthy ecosystems and landscapes are the precondition for sustainability, and that achieving sustainability often requires fundamental shifts in governance structures, values, as well as an examination of the rights and responsibilities associated with private property.

At the international policy level, the Millennium Development Goals (MDGs) reflect the broadest aspirations of humankind to move towards sustainability. While goals such as the reduction of poverty, increased literacy, provision of adequate drinking water, etc. are laudable, they are not likely to be achievable in the absence of restoration of full functionality (i.e., health) to the Earth's ecosystems. Thus, to existing MDGs should be added an additional, and perhaps, primary goal—namely, the restoration of the health of the biosphere and its ecosystems. If we fail to achieve this, it is most likely that we will continue to fall evermore short of the MDG targets.

## Conclusion

Although the call for "sustainability" in view of limits to conventional economic growth is now decades old, there is no evidence that the Earth's systems are becoming more sustainable. Rather, ecosystems and landscapes continue to deteriorate, as measured by the increased evidence of ecosystem distress syndrome (EDS), loss of resilience, loss of organization, and reduced productivity. Since "sustainability science" serves as a catalyst for encouraging new ideas that are essential to achieving a much-needed harmonization between human needs/aspirations and ecological constraints, ecosystem health should become one of its cornerstones.

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