Ecosystem Health Indicators

Improving the health of ecosystems is a long-term goal globally. Achieving this depends importantly on the establishment of meaningful ecosystem health indicators to identify critical drivers and pressures of ecological degradation and assess progress in addressing them. Indicators of ecosystem health and assessments based on them are essential to motivate both policy makers and the public to take the necessary actions to restore the health of the world's ecosystems.

Over the past half century, the concept of "health," long applied in reference to the vitality of individuals (humans as well as other species), has been extended to the higher levels of biological organization: populations, ecological communities, whole ecosystems, landscapes, and the biosphere. At each level, the metrics required to assess health differ. For example, the health of a population is not simply the summation of the health status of the individuals. New metrics are used that refer specifically to the status of an entire population. As for what constitutes ecosystem health, while there are a variety of definitions, nearly all of these comprise three basic elements: organization, vitality, and resilience. *Organization* refers to the structure of the ecosystem—the web of connections that link species with one another and with their environment. Loss of key structural properties of ecosystems—for example, disturbance to or removal of soil, coral, or stream bed—may cripple the ecosystem's capacity to maintain its biotic assemblage. *Vitality* refers to the overall metabolism of the ecosystem, that is, its capacity to maintain the flow of energy from primary producers (plants) to primary (herbivores) and secondary (carnivores) consumers, as well as its capacity to sustain the essential nutrient cycles. *Resilience* refers to the capacity of an ecosystem to recover from perturbations such as those caused by floods, fire, insect infestations, drought, and the like. While such perturbations cause short-term disruptions in community structure and ecological functions (drought, for example, may completely eliminate above-ground biota), healthy ecosystems are able to bounce back from these natural disturbances. For some perturbation-dependent ecosystems, natural disturbances such as forest fires or floods are an essential part of the dynamics to maintain the health of the system.

There is an ever-expanding list of metrics that are used to evaluate the health of ecosystems. Many of these are useful across the full range of the world's ecosystems. No single metric is adequate to evaluate health; rather, a suite of well-chosen indicators are employed. For indicators to be of service, it is necessary to establish the normal range of values for each indicator for the particular type of ecosystem under evaluation, for example, the normal range of primary productivity for grassland in a particular region, or the range of diversity of avian species in an old-growth temperate rain forest. Common indicators for a wide range of ecosystem health assessments include progressive dominance by opportunistic species, progressive invasion of nonlocal or non-native species, shifts in community structure, loss of substratum, disruption of nutrient cycling, and progressive loss of ecosystem services (attributes valued by humans) (Rapport and Whitford 1999, 193–203).

From Indicators to Indices

In descriptions of the overall condition of systems with large numbers of components, it is tempting to look for possibilities to create indices that aggregate information from individual indicators. Indices are valuable when they have a strong logical and scientific basis that allows for the amalgamation of disparate sets of data. This has been successful in certain social applications, such as the widespread use of a consumer price index, where the interpretation of the index is clear. Indices have been created for a variety of environmental applications (e.g., water quality, air pollution). In evaluating the health of ecosystems, there have also been attempts to amalgamate various considerations into a single index that would convey a general message on the health of the system. An example is the construction of a Forest Capital Index (Rapport and Ullsten 2006, 268–290). Such indices may give a crude overview of the health of a system, but they are often problematic as tools of communication. They are difficult to conceptualize if they combine many indicators related to different aspects of ecosystem health and the weighting (explicit or implicit) of the indicators that form the index heavily influences the message that the index conveys.

History of Indicator Development

The roots of indicator development are embedded in the history and prehistory of human culture. A remark attributed to Plato suggests that thousands of years ago people understood that certain modifications of agricultural drainage systems had adverse consequences for agricultural yields. Throughout the ages keen observers have taken note of correlations between human activity and ecosystem transformation. In the late seventeenth and early eighteenth centuries, when the rivers Thames and Rhine came under heavy stress from industrial waste, it was easy to recognize that foul smells, discolored waters, and local fish kills were a direct consequence of industrial activity.

In the twentieth century, the observations of naturalists, most notably those of Aldo Leopold in the 1940s, led to the realization that the consequences of human actions were rendering the land dysfunctional—resulting in what Leopold termed "land sickness." Among the worrisome signs Leopold observed in his native Wisconsin landscape were losses of native species; declines in biodiversity, soil fertility, and crop yields; reductions in biological productivity; increased presence of invasive species; and increased prevalence of diseases in both plants and animals. Several decades later, statistical agencies began to include the environment as part of their reporting functions, seeking a comprehensive framework that would relate human activities to environmental change. Statistics Canada's Stress-Response model provided a suitable template (Rapport and Friend 1979). Quickly adopted by the environmental secretariat of the Organization for Economic Cooperation and Development (OECD), this model, known today as the Pressure-State-Response (PSR) model, provides a taxonomy of anthropogenic stresses, ecosystem health indicators, and policy responses. Slightly modified, it is extensively used by the European Environment Agency for its state of environment reports.

A notable example of the application of the PSR model to assess ecosystem health is the retrospective assessment of the Baltic Sea undertaken by the Helsinki Commission (HELCOM 2010a). This report, *Ecosystem Health of the Baltic Sea,* is exemplary in showing the practicality of obtaining a suite of quantitative indicators of the health of a large-scale ecosystem and relating the state of health of this ecosystem to the suite of anthropogenic stresses impacting it. The value of this and many similar exercises—for example, evaluations of the health of the Laurentian Great Lakes (United States/Canada), Moreton Bay (Australia), Murray-Darling Basin (Australia), Bay of Fundy (Canada), Mesoamerican coral reefs, Florida Everglades—lies in providing a sound scientific basis for public policy geared to ameliorating environmental degradation.

Scale of Application

Indicators of the health of ecosystems may apply broadly across many ecosystems—or be more narrowly restricted to the characteristics of a particular ecosystem. For example, the prevalence of a particular forest insect pest, the mountain pine beetle, is a key indicator of the health of the coniferous forests of northern and central British Columbia, where an unprecedented outbreak (attributable to warmer winters and even age stands) has resulted in catastrophic loss of the forests of this region of Canada. This species, however, is specific to a particular ecological zone (mainly forests dominated by lodgepole pine, *Pinus contorta*). A more general indicator applicable to all forest ecosystems would be forest insect pest prevalence, without focusing on a specific species. Scaling up further, one could look at disease prevalence within an ecosystem. At this scale, the indicator could apply not only to forests but also to grasslands, lakes, marshlands, and so forth.

Scale is important in assessing ecosystem health. For example, monitoring the impacts of industrial sites is often limited to assessing the presence or absence of indicator species or potentially toxic compounds found in local biota. Such information may have little relevance beyond a very local domain. But when the pollution involves long-lived toxic substances that bio-accumulate in the food web, the consequences can eventually be reflected in ecosystem-wide degradation. Another example of widespread ecosystem-level impacts from industrial pollution is acidification of lakes and streams. In the 1970s, the sulfur dioxide emissions from a smelter near Sudbury, Ontario, were responsible for transforming a once-healthy mixed deciduous/coniferous forest to a virtual moonscape, eliminating forest cover and most vegetation on some 46,000 hectares, and in addition causing the acidification of more than seven thousand lakes in the region.

Quantitative Indicators for Ecosystem Health

An indicator is more than just the actual variable for which data is available. Massive algal blooms in a lake or a coastal area do not simply tell us that there are plenty of algae in the water; they also indicate that excessive nutrients are entering the water body due to either poor sewage treatment or unsustainable farming practices that waste nutrients. In a similar way, changes in bird populations can be linked with transformations in forests: the decline of species associated with old-growth forest indicates losses of particular habitats.

Why would one want to quantify the health of an ecosystem? Quantified or quantifiable measures of health and health change make it possible to evaluate actions that may improve or degrade health. By tracking the quantitative health estimate together with quantitative information on anthropogenic stresses, one may eventually be able to provide prescriptive information on what to do or not to do. For example, what intensity of fishing is compatible with sustaining the health of a lake or a sea area? What kinds of forestry practices are consistent with maintaining a healthy forest (that is, not just sustaining timber extraction)?

Traditional resource management has tried to approach these questions by examining each single exploitable resource as an independent entity for which it is possible to determine a maximum sustainable yield. This approach has proven to be inadequate in that, by focusing only on the resource, it neglects the interactions between different components of the ecosystem and thus falls short of assessing the overall health of the ecosystem. The maximum sustainable yield for a single species may actually be disastrous for the health of the whole ecosystem. Intense exploitation of forage fish may cause bird populations to decline; sustainable-yield harvesting of timber can lead to the demise of species dependent on dead wood.

A suite of quantitative indicators is required in order to cover the many facets of ecosystem health. For example, for the HELCOM retrospective assessment of the Baltic Sea, quantitative estimates of nutrient status, contaminant levels, state of fish stocks, and biodiversity were required. This allowed for the assessment of the overall ecosystem health of the Baltic, as well as the health of its sub-basins and regions. The value of such assessments lies in identifying critical issues that need immediate attention if the health of the ecosystem (upon which human well-being vitally depends) is to be improved. Similar approaches have been taken in North America's Laurentian Great Lakes, and yearly reports are published on a suite of ecosystem health indicators for each of the lake basins. These indicators and assessments provide guidance for both management and policy.

Monitoring Ecosystem Health

Monitoring the health of ecosystems requires not only careful selection of a suite of key indicators, but also attention to the practicality of gathering high-quality, reliable data on their status and trends, and the establishment of valid baselines (or normal ranges) in order to assess the health of the ecosystem. In some instances, this is relatively straightforward. For example, much can be learned about the health of the Baltic Sea from the abundance and distribution of an easily identified seaweed, bladderwrack (*Fucus vesiculosus*), found in the shallow waters of the Baltic Sea. The maximum depth at which this seaweed is found is limited by water transparency, and thus by the availability of light. Observing over time the depths at which this seaweed is found provides useful information on the overall eutrophic (nutrient) condition of the sea. Eutrophication (i.e., excess nutrients from sewage and agricultural runoff) is one of the main environmental issues in the Baltic. Monitoring for the bladderwrack serves double duty in that the seaweed provides habitat for many species, including many juvenile fishes. As its abundance increases, fish habitat improves, contributing to an improvement in the health of the entire ecosystem.

The baseline or reference level for each indicator is a crucial aspect of monitoring for ecosystem health. When it comes to anthropogenic synthetic pollutants such as polychlorinated biphenyls (PCBs), one can use zero as a reference level, but in addition one would also need to know the thresholds after which adverse effects begin to appear. The classical approach is to experimentally determine a dose-response curve; "no effect concentrations" can be estimated from the curve. These thresholds may provide guidance for monitoring ecosystem health, but one should be aware that the values commonly refer to laboratory tests using single substances, whereas ecosystems are subject to cumulative effects of multiple stressors. Thus the threshold levels for adverse effect may be significantly lower than in laboratory experiments. In some cases, different stressors may have antagonistic effects, and then the actual thresholds for adverse effects on the ecosystem may be higher than those anticipated in laboratory studies.

The baseline for variables such as species abundance or size distribution is more difficult to determine. In some cases it may be possible to derive an estimate of the conditions of the ecosystem when it was in a pristine state before significant human intervention. With the exception of some remote ecosystems, this approach is not practical, however, because many ecosystems have evolved in constant interaction with humans. Owing to such difficulties, often more pragmatic approaches are called into play in evaluating the health of ecosystems. In the European Union (EU), the Water Framework Directive and the Marine Strategy Directive (both legal documents) have created obligations to specify what constitutes "good ecological status" for different water bodies. This has led to identification of variables and thresholds that relate to ecological status (which in principle is closely related to health throughout Europe). The goal of these directives is to stimulate action plans that will result in restoring all water bodies to a healthy condition.

Trade-offs and Challenges in Ecological Monitoring

One of the major challenges in the development of ecosystem health indicators is finding indicators that can serve as "early warning" signals for ecosystem degradation. Too often these indicators are only discovered after the damage is done, and it is too late or economically impractical to reverse course. Generally, it is only in retrospect that changes in a seemingly insignificant part of the ecosystem might be linked to major ecosystem-wide consequences. For example, in the 1950s, mayflies (*Hexagenia* spp.), which became very abundant in spring breeding swarms along Lake Erie shores (United States/Canada), suddenly disappeared. While their disappearance did not go unnoticed (their swarming was always a nuisance to residents and resulted in slippery and thus hazardous driving conditions), the more far-reaching consequences for the health of Lake Erie were not immediately foreseen. Yet, in retrospect, the disappearance of mayfly larvae was one of the first signs of degradation of Lake Erie—for the disappearance of the larvae in the lake's bottom waters was due to nutrient loading and the creation of a seasonal dead zone in these bottom waters. In other situations, for example in lakes impacted by acidification, the earliest indicator that the level of acidification is negatively affecting the health of the lake might be found in altered behaviors of sensitive species. Yet, monitoring for behavioral changes in individuals or populations is extremely costly and generally impractical.

Another major challenge is the cost of acquiring synoptic data. With the rapid development of remote sensing imagery, and ever more numerous applications to ecosystem assessment, these costs are rapidly declining. Remote sensing is particularly well suited to spatial data on the extent of forest cover, forest tree composition, extent and location of wetlands, condition of grasslands, including surrogate measures for primary production, large-scale algal blooms, shoreline degradation, and the like. Yet for many variables that are essential in the evaluation of the health of ecosystems (such as fish stocks, water chemistry, soil biota, invasive species, disease prevalence, and so forth), remote sensing is of limited service. Intensive and often costly on-the-ground sampling is still required. In such cases, budgets require trade-offs among the number of variables being monitored, the frequency of data collection, and the intensity of the sampling design. All too often, such sampling results for large-scale ecosystems are far from ideal. Careful planning is therefore needed to combine different types of data collection so as to produce reliable indicators. It is particularly demanding to capture transient events that may reveal early stages of the degradation of the ecosystem health.

Outlook for the Coming Decades

The general goal to improve and secure the health of ecosystems has become widely accepted. For example, in the Helsinki Commission's first retrospective assessment of the state of the Baltic Sea, ecosystem health was the explicit focus. An emphasis on healthy ecosystems is also incorporated into the long term vision for the International Union for the Conservation of Nature, the strategy for 2009–2013 of the European Environment Agency, assessments of many large-scale ecosystems such as grasslands in Inner Mongolia, catchments in Australia, tropical reef ecosystems, and forest ecosystems. It has been implicitly and explicitly expressed for both aquatic and terrestrial ecosystems, and it has been included in legal documents. At the same time, it is obvious that this is a long-term goal. Many of the world's ecosystems display all of the signs of ecosystem distress syndrome, the result of decades—in some instances, centuries—of cumulative anthropogenic stress. In many cases, it is unlikely that the damage done can be quickly repaired. Yet these difficulties should by no means dissuade society from its efforts to improve the health of the world's ecosystems.

Ecosystem degradation has engulfed large areas of the planet. Researchers argue that we may already be well into the sixth mass extinction of life. Desertification has taken over once-productive grasslands; the world's oceans have been vastly depleted of their natural bounty of wild fish stocks; and whole ecosystems, including the world's tropical coral reefs (hot spots of biodiversity), have become endangered and are at risk of extinction within this century. The Aral Sea, once the world's fourth-largest lake, has practically disappeared and has left in its wake a highly toxic environment in which millions of people still reside. Many ecosystems such as the Great Lakes and the Baltic Sea remain highly degraded, despite decades of efforts to restore their health. Unless and until there is widespread recognition that the very foundations for sustaining human and other life on the planet are rapidly eroding, it seems unlikely that the will to change course will arise.

Indicators of ecosystem health are capable of providing a robust measuring rod for assessing in which direction we are heading. Such indicators are an essential ingredient for addressing the situation, as it is not possible to act responsibly without a clear picture of what the state of ecosystems actually is. The other indispensible ingredient, however, is the political and social will to act on the findings. Ecosystem health indicators and assessments based on them can help policy makers and the public see the need to act to maintain and restore the health of ecosystems.

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See also Biological Indicators (*several articles*); Computer Modeling; Ecological Footprint Accounting; Fisheries Indicators, Freshwater; Fisheries Indicators, Marine; Genuine Progress Indicators (GPI); Global Environmental Outlook (GEO) Reports; Human Appropriation of Net Primary Production (HANPP); Index of Biological Integrity (IBI); Land-Use and Land-Cover Change; Ocean Acidification—Measurement; Remote Sensing; Systems Thinking

Further Reading

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