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An Overview of Coastal Environmental Health Indicators

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ABSTRACT

Discussions of the coastal environment and its health can be improved by more precise use of terms and clarification of the relationship, if any, between the health of ecosystems and the risks to human health. Ecosystem health is seldom defined and, in any case, has to be regarded in different terms than human health. Ecosystem health should embody both the structure and function of the ecosystem. One attractive concept is to define the health of ecosystems in terms of their vigor, organization and resilience. From that perspective, the health of an ecosystem is reduced if it becomes a less vigorous producer of valuable living resources, less diverse and organized, and more susceptible to and slower to recover from stress. Useful indicators of ecosystem health should reflect these properties, but also be supported by understanding of cause and effect relationships generated through research. Significant challenges remain in the integration of indicators in terms of both their interrelationships and holistic significance. There is also a need to develop indicators that are relevant to emerging threats to coastal ecosystems.

Key Words: ecosystem health, coastal environments, vigor, organization, resilience, indicators

INTRODUCTION

There is widespread agreement among both scientists and members of the general public that many coastal environments are in poor health. Just what is meant by "health" and how to measure it are a different matter, with no commonly accepted criteria or benchmarks. To many members of the public and medical profession, a principal concern is the risk posed to humans from exposure to pathogens or toxicants in the coastal environment or in seafood. To others, the

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health of coastal environments may mean the ability of the ecosystem to support fisheries, provide clean waters, or assure a diverse biota.

This overview offers a perspective on the current status of defining and measuring the health of coastal environments, reflecting in particular on the presentations made on this subject at the U.S. Environmental Protection Agency's (USEPA's) National Health and Environmental Effects Research Laboratory Symposium on "Indicators in Health and Ecological Risk Assessment" and the associated papers appearing in this volume. In particular, we discuss the relationship between human and ecosystem health, propose a model for describing ecosystem health, assess criteria for useful indicators of ecosystem health, and examine the relevance of commonly measured indicators to perceived emerging risks for coastal environments.

LINKING HUMAN AND ECOSYSTEM HEALTH

There is growing evidence that many disturbances of ecosystems, such as pollution, overharvesting, physical disruption, or climate forces, are associated with increased frequency or virulence of diseases of aquatic organisms (Harvell *et al.* 1999). However, some disturbances, like harmful algal blooms, hypoxia, and coral bleaching, contribute to, rather than cause, disease. The analysis of "emerging diseases as indicators of change" is an approach that considers human and ecological health in the same context (HEED 1998; Sherman and Epstein 2001; Sherman 2001) under the assumption that ecosystem disturbances are the driving forces. While this connection is important to make, the approach must be examined carefully within a risk assessment context. One typically finds that, in areas of extreme pollution or environmental degradation, the health of both humans and aquatic organisms are at risk. However, human health risks are not associated always with coastal degradation, and sometimes significant human health risks arise in coastal environments considered to be quite 'healthy'.

It is clear that human health may be threatened either by consumption of fish and shellfish contaminated with algal biotoxins, toxic chemicals, and microbial pathogens or by direct exposure to these pathogens or biotoxins. However, the relationship of these exposure conditions to the productivity or integrity of the ecosystem, its 'health', is seldom clear and straightforward. De Rosa and Hicks (2001) discuss risks to human health from the bioaccumulation of PCBs in fish from environmental contamination that may have effects on the aquatic communities. But these community-level effects have little or no relationship to actual human exposure. In another example, Tamplin (2001) reports that outbreaks of diseases associated with species of Vibrio bacteria (including cholera) have been linked to environments with warm water temperature, high organic load and plankton blooms, but concludes that temperature rather than pollution is the most important factor determining an outbreak. In summary, there is no overwhelming evidence that degraded coastal ecosystems are always associated with greater risks to human health.

ECOSYSTEM HEALTH

The metaphor of the "health" of an ecosystem as an analog for the health of a human being has been used for over a half century, at least since Aldo Leopold

(1941) wrote about "land sickness." However, ecosystem health is in practice seldom defined and there are significant limitations, both theoretical and practical, in the application of this concept in the same way we understand and measure human health (Costanza 1992; Ehrenfeld 1995). The study of human health focuses on various components of the individual while ecosystem health deals with the interactive mosaic of individuals, populations and communities. In many respects, ecosystems tend to be less constant and homeostatic than is the case for the human body. We are less practiced at defining the normal ranges of ecosystem states than physiological or immunological states of a human. And, it is less obvious that many observed changes in any particular ecosystem state are good or bad. Moreover, the same change in an ecosystem can be good for some, bad for others. Implicit in the concept of health is how humans value the performance of an ecosystem in terms of the goods and services it provides. Nonetheless, there have been significant recent advances in the conceptualization and measurement of ecosystem health (Costanza 1992; Rapport 1995; Rapport *et al.* 1998; Campbell 2000) that allow us to describe and measure the health of coastal ecosystems more rigorously.

Any useful notion of ecosystem health should involve both the structure (the species and populations involved) and function (the flow of energy and materials) of the ecosystem. Costanza (1992) reviewed the limitations of various concepts of ecosystem health and concluded that ecosystem health should include three components: vigor, organization, and resilience (V-O-R). Vigor embodies the throughput or productivity of the ecosystem. Organization represents not only species diversity, but also the degree of connectedness of the constituent species (complexity of trophic and other interactions). Resilience refers to an ecosystem's ability to maintain structure and patterns of behavior in the face of stress. A resilient ecosystem can withstand sustained or repeated stress.

A healthy ecosystem, then, is one that is actively producing (V), maintains its biological organization over time (O), and is resilient to stress (R). Costanza (1992) also points out that ecosystem health is a normative concept, involving interpretation based on human values of the overall ecosystem. For example, the gross productivity of an estuary may increase as a result of eutrophication, but this increase may be in the form of rapidly growing, small organisms at the expense of larger, more long-lived organisms that are more valuable to humans. From this perspective, the health of the estuary deteriorates as a result of nutrient over-enrichment and concomitant reduction of light availability and loss of habitats that produce complexity. In the case of Chesapeake Bay, this deterioration has resulted in an ecosystem that produces less valuable fish and shellfish, is less diverse and well organized, and slower to recover from stress (Ulanowicz 1997).

Although the V-O-R model of ecosystem health is not yet broadly accepted in either the scientific or management communities, it does provide a multidimensional framework that integrates ecosystem structure and function. In other words, it reflects not only what an ecosystem looks like, but also how it is organized and what it produces. Such a framework is sorely needed as a means of integrating and interpreting the many attributes we routinely measure as indicators of ecosystem health. A good analogy is that pulse rate is a good indicator for human health not only because it is easily measured, but also because it reflects an integration of bodily functions. In addition, we have a wealth of information underlying its usefulness in diagnosis.

The V-O-R model also provides a framework for understanding and accounting for the differences among ecosystems and the dynamic nature of any given ecosystem, providing more flexible references for ecosystem health standards. For example, Figure 1 presents a conceptualization of ecosystem health over a range of vigor, organization and resilience levels. Costanza and Mageau (1999) demonstrate how indices of these properties can be calculated from network analysis and compared among ecosystems and over time.

Flexible standards of ecosystem health are necessary because of substantial differences in how coastal ecosystems respond to stressors. Nixon *et al.* (2001) offer an excellent example of how very shallow ecosystems, such as coastal lagoons, respond very differently to nutrient enrichment than deeper estuaries. The behavior of the latter can be well predicted by Vollenweider-type models, while the responses of lagoonal systems are more nonlinear and geographically variable, influenced greatly by the biology of vascular plants and their interactions with epiphytes. Under these conditions, uniform standards, either of water quality or ecosystem health, are doomed to failure.

Picking up on the health metaphor, Steevens *et al.* (2001) suggest a physician-like approach to the patient (a coastal ecosystem) that involves diagnosis, prognosis, treatment, and prevention. However, in practice it is often difficult to relate a symptom to a cause, and thus a cure. They noted that in the northern Gulf of Mexico 37% of the estuarine area was diagnosed having degraded benthic communities; 90% of that area also had one or more significant environmental stressors such as sediment contamination, sediment toxicity, hypoxia, or nutrient enrichment. But it is unclear which of these, if any, was the cause of the degradation. Within Pensacola Bay they similarly noted the coincidence of benthic community degradation with inputs of bioaccumulative toxicants, nutrients and organic materials. Reducing toxic inputs might not improve the health of the estuarine ecosystem if nutrient and organic inputs were more directly responsible.

Given our current level of understanding, ecosystems are more unpredictable than the human body. Diagnosis, prognosis and treatment of human health have had the benefit of experience and research over a much longer time than ecosystem health. In fact, the current U.S. investment in research to improve the diagnosis, prognosis and treatment of human health is about two orders of magnitude greater than for ecosystems. Our point is not for lamentation, but to caution against simplistic notions that even the diagnosis of ecosystem health based simply on indicators is straightforward; prognosis and treatment can be even more problematic. In addition to monitoring of indicators, research is needed to unravel cause and effect and to develop effective ecosystem therapies, medicinals and preventions.

INDICATORS OF ECOSYSTEM HEALTH

Vigor, organization, and resilience are easier to describe in theory than to measure in practice. Consequently, the way we try to monitor the health of a coastal ecosystem is to measure selected indicators, or small pieces of the ecosystem, to represent the whole. Some of these indicators reflect processes or rate measure-

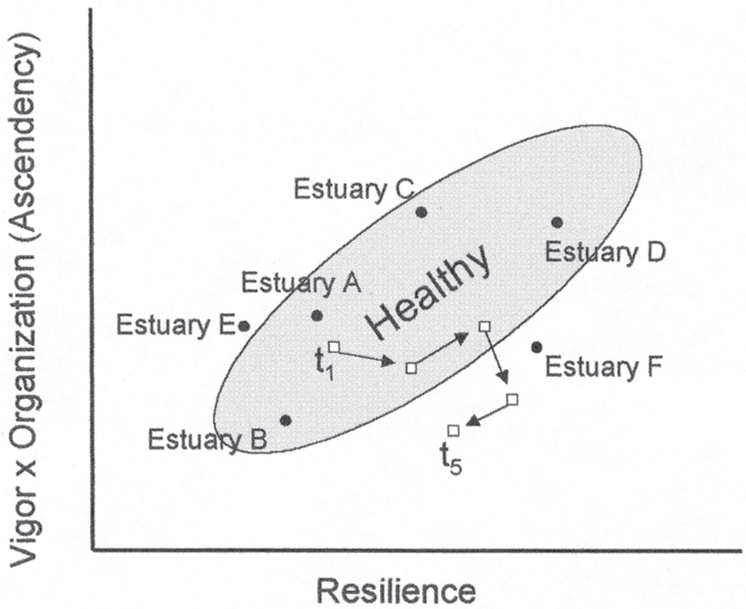

Figure 1. A conceptual diagram of ecosystem health as a function of vigor and organization (the product of which is termed ascendancy) and resilience, showing how different estuaries may exhibit different V-O-R properties of ecosystem health and how V-O-R properties may change over time ($t_1 \rightarrow t_5$). Based on Costanza and Mageau (1999).

ments (primary production, flux of nutrients from bottom sediments, or yield as reflected by harvests), but most are measurements of states (temperature, light transmission, concentrations of salinity, nutrients, dissolved oxygen, and chlorophyll) or biological structure (biomass, community composition and diversity, incidence of diseases, *etc.*).

Some efforts have been directed to application of measures of biotic integrity (Karr 1991) that relate the organization of parts of the ecosystem to a norm, reflecting what is considered the "healthy" condition. For example, indices of biotic integrity have been developed and applied for the macrobenthic communities in specific ecosystems, such as the Chesapeake Bay (Dauer 1993; Weisberg *et al.* 1997), or over broader regions (Paul *et al.* 1999; Steevens *et al.* 2001), which reflect diversity, trophic structure, and life history characteristics of species in the community to that presumed to characterize the unaltered benthos under those salinity and sediment conditions.

But we need to advance the state-of-the-art by developing additional indicators of the condition and functioning of other living parts of the ecosystem and by grounding these new indicators in the context of ecosystem health as represented in V-O-R or some other suitable construct. In general, better indicators of ecosystem function are needed to complement those of status. A particular challenge is the representation of more dynamic properties of ecosystems, ranging from plankton production to recruitment of fish populations that are affected by important 21st century issues such as eutrophication and over fishing. *In situ*, remote and other new technologies offer opportunities in that regard (Boesch 2000).

It is important to keep in mind the purpose of an indicator during its selection or design. Indicators designed for comparisons within or among broad regional areas, such as those used in the Environmental Monitoring and Assessment Program (EMAP) (USEPA 1998, 1999) and the Report on the State of the Nation's Ecosystems (Heinz Center 1999), are generally more simplified (in terms of abstraction and spatial and temporal detail) than is desired for management purposes within a specific estuary or coastal ecosystem. In addition, monitoring of ecosystem health may have differing and multiple uses and objectives, including describing trends, gauging the degree to which goals have been met, assessing the resource base, assuring precautionary protection, applying to the calibration and verification of models, providing the context for research hypothesis testing, informing the public, and supplying background information in response to emergencies (Boesch 2000). It is logical, then, that different indicators may be appropriate for different objectives.

Finally, development and testing are required if coastal health indicators are to be integrated: across environmental media (air-land-fresh waters-estuary-ocean), among resources (*e.g.*, water quality-habitats-living resources-human health), over space and time scales, and among monitoring, modeling and research programs (Boesch 2000). Wigand *et al.* (2001) propose a framework for integrating indicators of structure and function for coastal wetlands. Bertram (2000) reported on the progress in selection of indicators of ecosystem health for the Great Lakes through the State of the Lakes Ecosystem Conferences (SOLEC, http://www.on.ec.gc.ca/solec/). A broad suite of indicators for both the states and provinces is being evaluated for nearshore and open waters, coastal wetlands, nearshore terrestrial environments, land use, human health and human society. Lussier *et al.* (2001) illustrate how a geographic information system can be used to integrate data and public concerns on a watershed scale. Paul and DeMoss (2001) discuss integrated indicators for forests, streams and rivers, bird communities, and estuaries in the Mid-Atlantic Integrated Assessment. These are important efforts from which we are learning much. In the use of indicators in such holistic assessments, additional research and evaluation are needed on incorporating the relationships among indicators in the analysis and assembly rules and weighting in construction of aggregate indices.

EMERGING RISKS

Changes in coastal ecosystem risks present a grand challenge to those scientists and managers who are working hard to develop and apply indicators for the 21st century. We routinely measure toxicant levels in sediments or biota—such measures have become nearly pro forma indicators. While there remain problems with toxic substances in the environment, with the phasing out of the most threatening compounds such as DDT, PCB, and TBT and because of effluent treatment requirements, the threat of toxics to coastal ecosystem health is in general decreasing rather than increasing (Boesch *et al.* 2001). Other challenges, from climate change (Walker 2001; Barber *et al.* 2001) and large-scale modification of the nitrogen cycle (Vitousek *et al.* 1997) to nonindigenous species (Mack *et al.* 2000) and permanent loss of biodiversity (Naeem *et al.* 1999), now confront us. What we know how to measure does not always match up very well with the needs to address the threats to ecosystem health from these emerging concerns (Table 1).

There is much yet to accomplish in developing and applying effective indicators of coastal health. Indicators must be more effectively grounded within a concept of the health of ecosystems that embodies their functioning and sustainability, but we also must better understand the risks of these emerging threats in a way that supports prognosis and treatment.

Table 1. Traditional indicators compared with the emerging threats to coastal ecosystem health looking to the future.

What we currently measure	What we are concerned about from emerging threats
Contaminant levels	Irreversible habitat change with loss of productivity and biodiversity
Material inputs (*e.g.*, nutrients, sediments)	Modification of the N cycle
Water quality (*e.g.*, dissolved oxygen)	Watershed landscape conversion (a.k.a. urban sprawl)
Fish catch	Effects of climate variability and change
Extent of certain habitats (*e.g.*, wetlands)	Nonindigenous species
Community structure	Sustainable fishing
Toxicity biomarkers	Release of hormones and antibiotics
Indicators of human pathogens	Teleconnections (*e.g.*, atmospheric iron)

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