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# 14

# Toward an Operational Definition of Ecosystem Health

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Ecosystem health is a normative concept: a bottom line. It represents a desired endpoint of environmental management, but the concept has been difficult to use because of the complex, hierarchical nature of ecosystems. Without an adequate operational definition of the desired endpoint, effective management is unlikely. This chapter investigates some of the operational definitions of ecosystem health, weighs their advantages and disadvantages, suggests alternatives that synthesize these past definitions, and suggests research paths aimed at allowing these new definitions to be put into practice.

Concept definitions of ecosystem health can be summarized as:

- Health as homeostasis
- Health as the absence of disease
- Health as diversity or complexity
- Health as stability or resilience
- Health as vigor or scope for growth
- Health as balance between system components

All of these concepts represent pieces of the puzzle, but none is comprehensive enough to serve our purposes here. Hence I wish to elaborate on the concept of ecosystem health as a comprehensive, multiscale, dynamic, hierarchical measure of system resilience, organization, and vigor. These concepts are embodied in the term "sustainability," which implies the system's ability to maintain its structure (organization) and function (vigor) over time in the face of external stress (resilience). A healthy system must also be defined in light of both its context (the larger system of which it is part) and its components (the smaller systems that make it up).

## WHY DO WE NEED CONCEPTS FOR MANAGING ECOSYSTEMS?

All complex systems are, by definition, made up of a number of interacting parts. In general, these components vary in their type, structure, and function within the whole system. Thus a system's behavior cannot be summarized simply by adding up the behavior of the individual parts. Contrast a simple physical system (say an ideal gas) with a complex biological system (say an organism). The temperature of the gas is a simple aggregation of the kinetic energy of all the individual molecules in the gas. The temperature, pressure, and volume of the gas are related by simple relationships with little or no uncertainty. An organism, however, is composed of complex cells and organ systems. The state of an organism cannot be surmised simply by adding up the states of the individual components, since these components are themselves complex and have different, noncommensurable functions within the overall system. Indicators that might be useful for understanding heart function—pumping rate and blood pressure, for instance—are meaningless for skin or teeth.

But to understand and manage complex systems, we need some way of assessing the system's overall performance (its relative "health"). The EPA has recently begun to shift the stated goals of its monitoring and enforcement activities from protecting only "human health" to protecting overall "ecological health." Indeed, EPA's Science Advisory Board (SAB 1990:17) recently stated:



> EPA should attach as much importance to reducing ecological risk as it does to reducing human health risk. These very close linkages between human health and ecological health should be reflected in national environmental policy. When EPA compares the risks posed by different environmental problems in order to set priorities for Agency action, the risks posed to ecological systems must be an important part of the equation.

Although this statement gives the concept of ecological health importance as a primary EPA goal, it begs the question of what ecosystem health *is*, while tacitly defining it as analogous to human health. The dictionary definitions of health are: "1. the condition of being sound in mind, body, and spirit; 2. flourishing condition or well-being." These definitions are rather vague. In order to meet the mandate for effectively managing the environment we must construct a more rigorous and operational definition of health that is applicable to all complex systems at all levels of scale, including organisms, ecosystems, and economic systems. As the preceding chapters make clear, there is a wide range of opinion about how to proceed with this daunting task. Some interesting possibilites have been proposed, however, and I think we are off to a good start.

In its simplest terms, then, health is a measure of the overall performance of a complex system that is built up from the behavior of its parts. Such measures of system health imply a *weighted* summation or a more complex operation over the component parts, where the weighting factors incorporate an assessment of the relative importance of each component to the functioning of the whole. This assessment of relative importance incorporates "values," which can range from subjective and qualitative to objective and quantitative as we gain more knowledge about the system under study. In the practice of human medicine, these weighting factors or values are contained in the body of knowledge and experience embodied in the medical practitioner.

Figure 1 shows the progression from directly measured "indicators" of a component's status, through "endpoints" that are composites of these indicators, to health with the help of "values." Measures of health are inherently more difficult, more comprehensive, require more modeling and synthesis, and involve less precision, but are more relevant than the endpoints and indicators from which they are built. It remains to determine which general approaches to developing these measures of health for ecosystems are most effective. I begin with a review of current approaches and end with a synthesis incorporating the best features of these systems along with some new ideas.

## CURRENT CONCEPTS OF ECOSYSTEM HEALTH

Concepts of ecosystem health can be derived by analogy with concepts of human health (Rapport 1989; Chapter 8 of this volume). Both human individuals and ecosystems are complex systems composed of interacting parts in a complex balance of interdependent function. But humans are warm-blooded, homeostatic systems and human physicians have a compendium of known

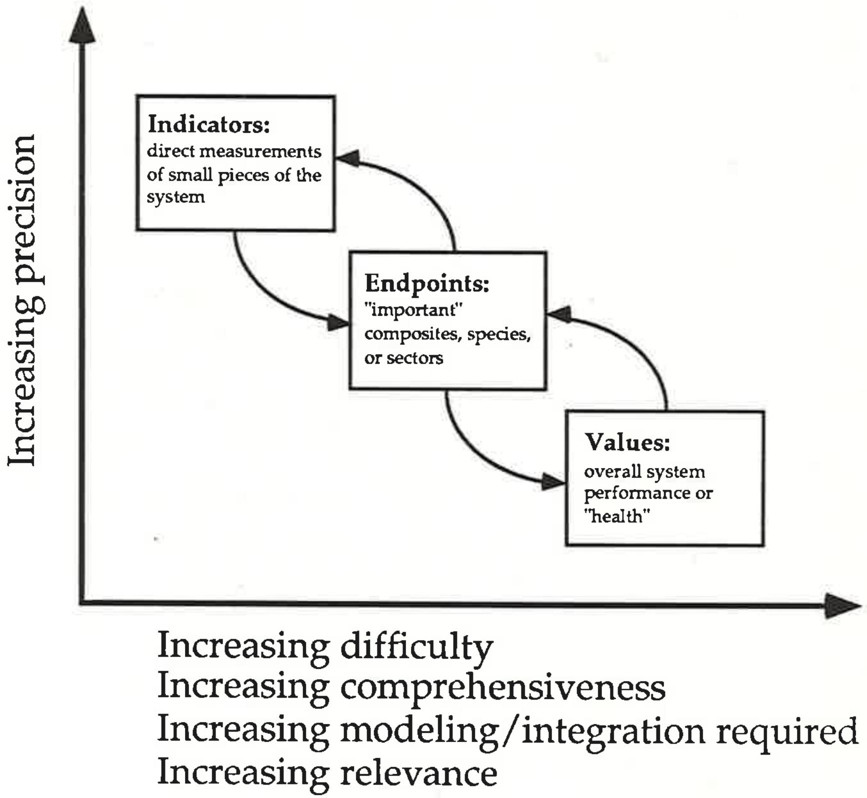


FIGURE 1. *Relationship of indicators, endpoints, and values*



diseases, a wide body of reference data on the "standard human," and many diagnostic tools (Schaeffer et al. 1988; Chapter 9 of this volume). None of these aids are available for ecosystems. There is, however, a large body of literature on the related concepts of ecosystem stability and resilience (reviewed in Pimm 1984 and Holling 1986). In the following discussion I make use of several terms and concepts that have emerged in this ecological literature over the past forty years. They are summarized and defined in Table 1 (an expanded version of a table appearing in Pimm 1984).

What we are after is a general concept of *complex system health* that draws on ideas from human health practice and ecosystem (and economic system) theory and practice but is equally applicable to evaluating the health of any complex system at any scale—from cells to organs to organisms to populations to ecosystems and economic systems.

### *Health as Homeostasis*

The simplest and most popular definition of system health is health as homeostasis: Any and all changes in the system represent a decrease in health. It is popular because it does not require a weighted synthesis of the raw indicators. If any one indicator is seen to change beyond the range of "normal variation," the system's health is deemed to have suffered. The only complication is differentiating internal natural variation from that induced by outside stress. This approach works moderately well for organisms, especially warm-blooded vertebrates, since they are homeostatic and there is a very large population from which to determine "normal ranges." But for ecosystems, economic systems, and other nonhomeostatic systems with small populations, it works less well or not at all.

First of all, we cannot assume that all change is bad (or at least not equally bad). Even in homeostatic organisms one must be able to attach some relative importance (based on overall system function or health) to each indicator in order to get any idea of *how*

TABLE 1. *Definitions of Key Variables*

| *Variable* | *Definition* |
|---|---|
| Stability | |
| Homeostasis | Maintenance of steady state in living organisms by use of feedback control processes. |
| Stable | A system is stable if and only if variables all return to initial equilibrium after being disturbed. A system is locally stable if this return applies to small perturbations and globally stable if it applies to all possible perturbations. |
| Sustainable | A system's ability to maintain structure and function indefinitely. All nonsuccessional (climax) ecosystems are sustainable, but they may not be stable. (See Resilience below.) Sustainability is a policy goal for economic systems. |
| Resilience | 1. How fast the variables return to equilibrium following perturbation; not defined for unstable systems (Pimm 1984). 2. A system's ability to maintain structure and patterns of behavior in the face of disturbance (Holling 1986). |
| Resistance | The degree to which a variable is changed following perturbation. |
| Variability | The variance of population densities over time or allied measures such as standard deviation or coefficient of variation (SD/mean). |
| Complexity | |
| Species richness | The number of species in a system. |
| Connectance | The number of interspecific interactions divided by possible interspecific interactions. |
| Interaction strength | The mean magnitude of interspecific interaction: size of the effect of one species' density on growth rate of another species. |
| Evenness | The variance of species abundance distribution. |
| Diversity indices | Measures combining evenness and richness with a particular weighting for each; one important member of this family is the information-theory index, *H*. |
| Ascendency | An information-theory measure combining average mutual information (a measure of connectedness) and the system's total throughput as a scaling factor (see Chapter 11). |
| Others | |
| Perturbation | Change to a system's inputs or environment beyond normal range of variation. |
| Stress | Perturbation with negative effect on a system. |
| Subsidy | Perturbation with a positive effect on a system. |

*Source:* Adapted from Pimm (1984) and Holling (1986).



*much* health has changed. Gaining ten pounds is not as bad as developing a heart murmur which is not as bad as developing cancer, even though all of these can be considered departures from homeostasis. Moreover ecosystems are complicated by the process of succession. If conditions change sufficiently, there will be replacement of one ecosystem with another that is better adapted to the new conditions. This represents radical change for the first system, and unless one can assess the relative value of the larger system before and after succession, then all successional changes must be considered harmful. But nature (even with no human intervention) is in a constant state of adjustment, change, and succession, not in a state of stasis or equilibrium. We must therefore look a little deeper for an adequate definition of ecosystem health.

### *Health as Absence of Disease*

Health is often defined as the absence of disease. But to operationalize this definition one must first define disease. The dictionary defines it as "any departure from health." Thus defining health as absence of disease just restates the problem in the negative. If we can define health, we can also define nonhealth or disease and vice versa. It also casts the problem in terms that are much too black or white. We desire a continuous measure of relative health, not a binary index of healthy or not healthy.

For organisms, a more useful definition of disease is possible: "a particular destructive process in the body, with a specific cause and characteristic symptoms; a specific illness, ailment, or malady." Disease can thus be thought of as a stress to the system, a perturbation with certain negative effects. One can catalog and eliminate all anthropogenic stresses on an ecosystem, but without an independent definition of health it is impossible to know which of these stresses really cause problems (are negative versus positive) and to what degree. If one uses the homeostatic definition of health, then any stress that causes any change in the system is a disease—and this seems much too severe and unrealistic. In fact, as C. S. Holling (1986, 1992) points out, ecosystem health may be related more to the ability of systems to *use* stress creatively than to their ability to resist it completely. More on this later.

*Health as Diversity or Complexity*

A third possible definition of ecosystem health is linked to the system's diversity or complexity. The idea is that diversity or complexity are predictors of stability or resilience and that these are measures of health. (See Table 1.) This linkage has been a subject of much controversy in the ecological literature, and the tide has turned several times. But because diversity is so easy to measure in ecosystems it has come to be a prime *de facto* indicator of health. According to Stewart Pimm (1984) there are several interesting aspects of the problem that have yet to be investigated. Recent advances in network analysis (Wulff et al. 1989; Chapter 11 of this volume) hold some promise in allowing a more sophisticated view of the *organization* of systems, not just their number of parts as in diversity measures. More on this later.

*Health as Stability or Resilience*

Stability and the related concept of resilience have much to recommend them as general measures of health. Healthy organisms have the ability to withstand disease organisms. They are resilient and recover quickly after a perturbation. Hence this leads to a definition of health as the ability to recover from stress. The greater this ability the healthier the system. A problem with this definition is that it says nothing about the system's operating level or degree of organization. A dead system is more stable than a live system because it is more resistant to change. But it is certainly not healthier. Thus an adequate definition of health should also say something about the system's level of activity and organization as well. There is a related, but in many respects more appealing definition of resilience as "the ability of a system to maintain its structure and patterns of behavior in the face of disturbance" (Holling 1986). This definition stresses the adaptive nature of ecosystems rather than the speed with which they can shrug off perturbations. Systems are healthy if they can absorb stress and use it creatively rather than simply resisting it and maintaining their former configurations. Southern pine forests, for example, are adapted to deal with frequent fires as a necessary part of their overall functioning. Efforts to suppress this stress are counterproductive and lead to larger, more destructive fires in the long run.



*Health as Vigor or Scope for Growth*

It has been hypothesized that a system's ability to recover from stress (or to utilize it) is related to its overall metabolism or energy flow (Odum 1971) or to its "scope for growth" (Bayne et al. 1987)—the difference between the energy required for system maintenance and the energy available to the system for all purposes. Both measures attempt to get at the system's capability to respond to generalized stress as well as its overall level of activity and organization and thus are one step deeper than stability or resilience alone. They are intended to be predictors of activity-weighted resilience and, ultimately, health.

*Health as Balance between Components*

Another concept that has wide acceptance in Eastern traditional medicine is the idea that a healthy system is one that maintains the proper balance between system components. This idea of balance is deeply ingrained in ecological theory as well, but it has usually been used as a general explanation for existing distributions (the ecosystem is in balance) rather in any predictive or diagnostic way. How do we know if the system is out of balance unless we have some overall indicator of health against which to judge?

## TOWARD A PRACTICAL DEFINITION

How can we create a practical definition of system health that is applicable with equal facility to complex systems at all scales? Let us first lay out the minimum characteristics of such a definition. First, an adequate definition of ecosystem health should integrate the concepts of health mentioned above. Specifically it should be a combined measure of system resilience, balance, organization (diversity), and vigor (metabolism). Second, the definition should be a comprehensive description of the system. Looking at only one part of the system implicitly gives the remaining parts zero weight. Third, the definition will require the use of weighting factors to compare and aggregate different components in the system. It should use weights for components that are linked to the functional dependence of the system's sustainability on the components, and the weights should be able to vary as the system changes to account for "balance." And fourth, the definition should be hierarchical to account for the interdependence of various time and space scales.

At a recent workshop attended by a wide range of participants including scientists, philosophers, managers, environmentalists, and industry representatives the following working definition of ecosystem health was arrived at (see the Introduction to this volume): An ecological system is healthy and free from "distress syndrome" if it is stable and sustainable—that is, if it is active and maintains its organization and autonomy over time and is resilient to stress. Ecosystem health is thus closely linked to the idea of sustainability, which is seen to be a comprehensive, multiscale, dynamic measure of system resilience, organization, and vigor. This definition is applicable to all complex systems from cells to ecosystems to economic systems (hence it is comprehensive and multiscale) and allows for the fact that systems may be growing and developing as a result of both natural and cultural influences. According to this definition, a diseased system is one that is not sustainable and will eventually cease to exist. The time and space frame are obviously important in this definition. Individual organisms are not sustainable indefinitely, but the populations and ecosystems of which they are part may be sustainable indefinitely. Distress syndrome refers to the irreversible processes of system breakdown leading to death (Rapport 1981). To be healthy and sustainable, a system must maintain its metabolic activity level as well as its internal structure and organization (a diversity of processes effectively linked to one another) and must be resilient to outside stresses over a time and space frame relevant to that system.

What does this mean in practice? Table 2 lays out the three main components of this proposed concept of system health (resilience, organization, and vigor) along with related concepts and measurements in various fields.

The following preliminary form for an overall system health index (HI) is proposed:

$$HI = V*O*R$$

where: $HI$ = system health index, also a measure of sustainability



TABLE 2. *Indices of Vigor, Organization, and Resilience in Various Fields*

| *Component of health* | *Related concepts* | *Related measures* | *Field of origin* | *Probable method of solution* |
|---|---|---|---|---|
| Vigor | Function<br>Productivity<br>Throughput | GPP, NPP, GEP<br>GNP<br>Metabolism | Ecology<br>Economics<br>Biology | Measurement |
| Organization | Structure<br>Biodiversity | Diversity index<br>Average mutual information<br>predictability | Ecology<br><br>Ecology | Network analysis |
| Resilience | | Scope for growth | Ecology | Simulation modeling |
| Combinations | | Ascendancy | Ecology | |

$V$ = system vigor, a cardinal measure of system activity, metabolism, or primary productivity

$O$ = system organization index, a 0–1 index of the relative degree of the system's organization, including its diversity and connectivity

$R$ = system resilience index, a 0–1 index of the relative degree of the system's resilience

This formulation leads to a comprehensive index incorporating the three major components outlined above. In essence, it is the system's vigor or activity weighted by indices for relative organization and resilience. In this context, eutrophication is unhealthy in that it usually represents an increase in metabolism that is more than outweighed by a decrease in organization and resilience. Artificially eutrophic systems tend toward lower species diversity, shorter food chains, and lower resilience.

Naturally eutrophic systems have developed higher diversity and organization along with higher metabolism and are therefore healthier. To operationalize these concepts (especially organization and resilience) the *HI* will require a heavy dose of systems modeling. We turn now to a summary of the available tools.

*Network Analysis*

Ecology is often defined as the study of the relationships between organisms and their environment. The quantitative analysis of interconnections between species and their abiotic environment has therefore been a central issue. The mathematical analysis of interconnections is important in other fields as well. Practical quantitative analysis of interconnections in complex systems began with the economist Wassily Leontief (1941) using what has come to be called input/output (I-O) analysis. Recently these concepts, sometimes called flow analysis, have been applied to the study of interconnections in ecosystems (Hannon 1973, 1976, 1979, 1985a, 1985b, 1985c; Costanza and Neill 1984). Related ideas were developed from a different perspective in ecology, under the heading of compartmental analysis (Barber et al. 1979; Finn 1976; Funderlic and Heath 1971). Walter Isard (1972) was the first to attempt a combined ecological/economic system I-O analysis, and combined ecological/economic mass-balance models have been proposed by several others (Daly 1968; Cumberland 1987). We refer to the total of all variations of the analysis of ecological and economic networks as *network analysis.*

Network analysis holds the promise of allowing an integrated, quantitative, hierarchical treatment of all complex systems, including ecosystems and combined ecological/economic systems. One promising route is the use of "ascendancy" (Ulanowicz 1980, 1986) and related measures (Wulff et al. 1989; Chapter 11 of this volume) to measure the degree of organization in ecological, economic, or any other networks. Measures like ascendency go several steps beyond the traditional diversity indices used in ecology. They estimate not only how many different species there are in a system but, more important, how those species are organized. This kind of measure may provide a necessary input for a quantitative and general index of system health applicable to both ecological and economic systems.

Another promising avenue of research in network analysis has to do with its use for "pricing" commodities in ecological or economic systems. The mixed-units problem arises in any field that tries to analyze interdependence in complex systems that have many different types and qualities of interacting parts. Ecology and economics are two such fields. Network analysis in ecology has avoided this problem in the past by arbitrarily choosing one



commodity flowing through the system as an index of interdependence (carbon, enthalpy, nitrogen, and the like). This strategy ignores the interdependencies between commodities and assumes that the chosen commodity is a valid tracer for relative value or importance in the system. This assumption is unrealistic and severely limits the comprehensiveness of an analysis whose major objective is to deal comprehensively with whole systems.

There are evolving methods for dealing with the mixed-units problem based on analogies to the calculation of prices in economic input/output models. Starting with a more realistic commodity-by-process description of ecosystem networks that allows for joint products, one can use *energy intensities* to ultimately convert the multiple commodity description into a pair of matrices that can serve as the input for standard (single-commodity) network analysis. The new single-commodity description incorporates commodity and process interdependencies in a manner analogous to the way economic value incorporates production interdependencies in economic systems (Costanza and Hannon 1989; Chapter 12 of this volume). This analysis would allow objective valuation of components of ecosystems and combined ecological/economic systems as a complement to subjective evaluations and better overall measures of *vigor* and *organization* in the system.

*Simulation Modeling*

Evaluating the health of complex systems demands a pluralistic approach (Norgaard 1989, Rapport 1989) and an ability to integrate and synthesize the many different perspectives that can be taken. Probably no single approach or paradigm is sufficient because, like the blind men and the elephant, the subject is too big and complex to touch it all with one limited set of perceptual tools. Rather, we must extend our view to cover the diversity of approaches that may shed light on the problem and must also develop the ability to use *all* of the available light to understand the system.

We need an integrated, multiscale, transdisciplinary, and pluralistic approach to quantitative modeling of systems (including organisms, ecosystems, and ecological/economic systems). While this approach has frequently been suggested (Norgaard 1989), it is difficult to operationalize with traditional funding mechanisms. Such an approach would allow the relationships between scales and modeling approaches to be directly investigated and would result in a deeper understanding of the systems under study. It would produce new ways of *scaling*—or using information at one scale to build understanding and models at other scales. This kind of scaling is essential to developing quantitative measures of system health, especially in addressing the resilience component of the system health index proposed here.

Quantifying resilience implies an ability to predict the dynamics of the system under stress. Predicting these ecosystem impacts requires sophisticated computer simulation models that represent a synthesis of the best available understanding of the way these complex systems function (Costanza et al. 1990). Beyond its use in health indices, this modeling capability is essential for regional ecosystem management and also for modeling the response of regional and global ecosystems to regional and global climate change, sea level rise, acid precipitation, toxic waste dumping, and a host of other potential impacts. Several recent developments make this kind of modeling feasible—not only the improved accessibility of extensive spatial and temporal data bases from remote sensing, aerial photography, and other sources (including EPA's new EMAP program), but also advances in computer power and convenience that make it possible to build and run predictive models at the necessary levels of spatial and temporal resolution.

## CONCLUSION

There is no silver bullet that will allow us to assess ecosystem health quickly, cheaply, precisely, and without ambiguity. There is no health meter with probes that can be inserted into ecosystems to yield a digital readout of health. Assessing health in a complex system—from organisms to ecosystems to economic systems—requires a good measure of judgment, precaution, and humility, but also a good measure of systems analysis and modeling in order to put all the individual pieces together into a coherent picture. Human health assessment likewise requires systems analysis, but the compendium of known diseases available, the huge body of reference data on the "standard human," and many types of diagnostic tools available make human health assessment possible without resort to sophisticated computer modeling. Not



that it does not require sophisticated analysis, but this analysis is embodied in the "expert system" of medical practitioners. To generalize this expertise and apply it to all kinds of systems requires systems modeling.

I have proposed a general index of system health made up of three components: vigor, organization, and resilience. Vigor can be measured directly in most cases. I have suggested that network analysis and simulation modeling are two of the most promising avenues for the development of the organization and resilience components of the proposed index. Both are relatively expensive to implement because of their large data requirements. But developments like EPA's Environmental Monitoring and Assessment Program (EMAP) that are designed to collect much of the data necessary to implement these analyses, along with remote sensing data and more capable and friendly computers, make implementing these methods finally feasible.

The idea is also amenable to direct empirical testing. One approach might be to apply various versions of the health index to systems for which we already have general agreement on health status—for example, humans or other organisms. One could then see which version did the best job of replicating our agreed-on health rankings in these systems as a test of their effectiveness. The best indices could then be applied to ecological systems with at least some confidence that they do represent the general health of the system. None of this will be easy or simple, but it is time to begin the messy, difficult, and absolutely essential task of assessing the health of ecological systems.

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