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A CRITIQUE OF ECOSYSTEM HEALTH CONCEPTS AND INDEXES

GLENN W. SUTER II
Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

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Abstract – Because people wish to preserve their health and do something equivalent for ecosystems, the metaphor of ecosystem health springs to mind. This paper presents the argument that it is a mistake for environmental scientists to treat this metaphor as reality. First, the metaphor fails because it misrepresents both ecology and health science. Ecosystems are not organisms, so they do not behave like organisms and do not have properties of organisms such as health. Also, health is not an operational concept for physicians or health risk assessors because they must predict, diagnose, and treat specific states called diseases or injuries; they do not calculate indexes of health. Second, attempts to operationally define ecosystem health result in the creation of indexes of heterogeneous variables. Such indexes have no meaning; they cannot be predicted, so they are not applicable to most regulatory problems; they have no diagnostic power; effects on one component are eclipsed by responses of other components; and the reason for a high or low index value is unknown. Their only virtue is that they reduce the complex array of ecosystem responses to various disturbances to one number with a reassuring name. A better alternative is to assess the real array of ecosystem responses so that causes can be diagnosed, future states can be predicted, and benefits of treatments can be compared.

Keywords – End point Ecosystem health Environmental health Indexes Index of biotic integrity (IBI).

INTRODUCTION

The phrase "ecosystem health" has recently gained considerable prominence in applied environmental science. It has been advocated as a goal for environmental regulation and management [1–4]. It is the subject of a new journal (*Journal of Aquatic Ecosystem Health*) and a recent workshop [5]. Although the concept has been criticized in passing and in part [6–8], it has not been seriously critiqued. It is time to examine this bandwagon carefully before it gains momentum. This paper begins with a consideration of the concept of ecosystem health in the abstract, considers the appropriateness of methods used to implement the concept, and ends with a discussion of alternative regulatory and management goals.

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THE ECOSYSTEM HEALTH METAPHOR

This discussion of ecosystem health has three premises: (1) Ecosystem health is a metaphor, not an observable property. Health is a property of organisms, and the use of the phrase "ecosystem health" is an attempt to draw metaphorically on the success and power of health science [3]. (2) Metaphors shape thoughts and actions. The power of poetry depends in large part on the power of metaphors to shape our perception of reality by causing two entities or ideas to appear equivalent. (3) Even if a metaphor has some heuristic power, it can be a mistake to reify and implement it. That your love "is like a red, red rose" does not mean that she/he should be planted, watered, and fertilized.

Ecosystem health is a poor metaphor

Because health is a property of organisms, "ecosystem health" implies that ecosystems are superorganisms. This implies in turn that ecosystems have consistent structures, regular development, homeostasis, tight integration, and distinct identities. This vision of ecosystems as superorganisms was implicit in Frederick Clements's theory of ecosystem development and in the models developed by some systems ecologists that included tight and deterministic regulatory processes. However, more detailed and longer term studies of ecosystems have shown that ecosystems do not have clear boundaries like the skin or cortex of an organism, they do not have consistent structures from one individual example to the next, they do not develop in a consistent predictable manner, and they do not have mechanisms like the neural and hormonal systems of organisms to maintain homeostasis [9–13]. Modern ecologists have devised theories of ecosystem development such as community gradients and mosaic cycles that have no correspondence to organism development, and many ecologists now treat ecosystems as rather arbitrarily defined entities that have heuristic and problem-solving value but not the clear identity of a medical patient. As Whittaker [13] bluntly wrote, "ecosystems are not organisms."

Even though ecosystems are not superorganisms, the ecosystem health metaphor might be appropriate in a weakened form if environmental management were like medicine. However, arguments presented below demonstrate that the metaphor presents a false impression of the nature of environmental management and can have unacceptable implications for management priorities. In addition, it is difficult to ensure that the metaphor will be used in a limited sense rather than in its strongest and most obvious sense, particularly when advocates of the term specifically argue that environmental management should be modeled on medicine [2–3], and some environmental groups view ecosystems as superorganisms [14].

Some reviewers of this paper have commented that the phrase "ecosystem health" is legitimate because it is equivalent to other common phrases such as "economic health." However, all uses of the term *health* refer to the root concept of human health; for economists the metaphor is derived from John Locke's and Adam Smith's concept of a national economy as a self-regulating entity with an ideal undisturbed "healthy" state. Each use of the metaphor must stand or fall on the basis of its individual appropriateness and utility. In particular, use of the health metaphor in economics or any other field does not legitimate the current use of the metaphor in environmental management, because different uses of a metaphor are not equivalent. Ecosystem health is treated as an operational goal of environmental management. In contrast, economic managers have well-defined goals such as full employment, positive balance of trade, and growth of the gross national product. Therefore, "economic health" is simply a figure of speech. If environmental managers are to imitate economists, they should imitate their clearly defined goals rather than try to turn their figures of speech into operational goals.

Unacceptable policy implications

"Values and behavior follow, which is to say, are implied in metaphors" [15]. Health is an overriding good. To sustain the health or organisms, organs and tissues are routinely sacrificed. It is not equally clear that guilds, populations, physical features, or individual organisms should be sacrificed to preserve whatever properties are deemed to constitute ecosystem health. As Norton [16] has pointed out, many environmental managers and members of the public would not agree that ecosystems are the organisms, and all lower level entities are expendable organs, tissues, or cells. If diversity is a measure of ecosystem health, does that mean that it is desirable to cut trees in a forest to create openings for early successional plants, to harvest dominant herbivores to increase the evenness of herbivore abundance, or to introduce exotic species? Even if we decide that ecosystem health is a preeminent goal, how do we define the patient [16]? Do we suppress a fire to save a forest ecosystem or sacrifice the forest ecosystem to save a regional prairie–forest mosaic ecosystem (i.e., is a forest a patient or an organ)? If taken seriously, a policy of maximizing ecosystem health could result in considerable environmental degradation at scales different from that of the designated patient.

Health is not a scalar operational property

In medicine and health science, health is an abstraction, not an operational property. In medicine physicians diagnose disease states (e.g., "You have bronchial pneumonia"), scales of lost structure (e.g., "20% of your left ventricular wall is dead"), or scales of lost function (e.g., "You have lost 30% of your kidney function"). They do not say "You are 60% healthy." Similarly, health risk assessors estimate that your risk of contracting cancer from a particular chemical exposure is 10^{-3}, not that your expected health is 10^{-3}. Hence, to create an operational property called ecosystem health is to misrepresent the health science to which the ecosystem health metaphor appeals for its power.

If health is not a scalar operational property, what is it? It is "a state of complete mental and social well-being . . . not merely the absence of disease" (World Health Organization, quoted in Rapport [2]). That is, it is subjective. Ecosystems do not have subjective states that they convey to us.

A stream does not tell us whether it feels better with a native sucker and minnow community or stocked with trout. Therefore, it has no health. To paraphrase DeAngelis et al. [7], ecological theory does not address the health of an ecosystem any more than celestial mechanics addresses the health of planetary orbits.

IMPLEMENTATION OF ECOSYSTEM HEALTH

Because health is not a property of ecosystems, implementation of the ecosystem health metaphor requires that a property be devised and named "ecosystem health." The obvious way to do this is to take a number of ecosystem properties and combine them into an index. This approach creates its own set of problems in addition to the problems inherent in the metaphor. Two such indexes will be used to illustrate those problems.

One is Karr's index of biotic integrity (IBI), which was presented as a measure of ecosystem health [1].* The IBI consists of 12 metrics of fish communities, including measures of abundance, trophic composition, species richness, species composition, and individual fish condition. These measures are scored into three classes relative to reference sites, and the scores are summed.

The other example is Costanza's ecosystem health index (HI) which is the product of system vigor, system organization, and system resilience [4]. System vigor is a cardinal measure of either primary production or system metabolism. System organization is a 0 to 1 index of the relative degree of organization of the system based on diversity or connectivity. System resilience is a 0 to 1 index of the ability of a system to resist or recover from damage. The resilience subindex is based largely on systems modeling.

Indexes of heterogeneous variables like the IBI & HI have the following potential faults.

Ambiguity

The first problem with indexes of heterogeneous variables is their ambiguity [17]. One cannot tell why such indexes are high or low. If an index is low, is it because all components are slightly damaged or because one component is severely damaged? Is the index low as a result of reduction in a societally valued component (e.g., the number of fish) or as a result of a component that is merely an "indicator" (e.g., percentage of hybrids)?

Eclipsing

In indexes of heterogeneous variables, low values of one component can be eclipsed by high values of another [17]. Some pairs of components are inherently likely to result in eclipsing. For example, it is a fundamental finding of epidemiology that increasing population density tends to increase the frequency of disease, but high density increases the IBI and high disease frequency lowers it. That is, the high density can eclipse the high disease frequency. One might argue that eclipsing is unlikely, because all of the components are likely to get worse simultaneously. However, where effects are due to toxic chemicals, specific modes of action are likely to have specific effects that may be eclipsed by other components of an index.

Arbitrary combining functions

Index values, and the decisions obtained from them, may be quite sensitive to the combining functions used to calculate them [17]. Additive, multiplicative, root mean square, and maximum/minimum operator functions, and weighted versions of them, may be used to combine the component variables, but in general no good rationale is given for the choice of function.

Arbitrary variance

The variance of indexes may be quite high due to the compounding of component variances. In addition, the distribution functions and other statistical properties of indexes of heterogeneous variables may be difficult to define. Typically, variance is viewed simply as an impediment to distinguishing between affected and reference sites. However, because chemical and physical agents may increase the spatial or temporal variance of biological parameters, the magnitude and pattern of variance in those parameters may be used to distinguish and define effects. But using the variance of an index for this purpose is questionable. Just as the relative magnitudes of the indexes bear no clear relationship to any biological response and are products of arbitrary combining functions, the variances of the indexes bear no clear relationship to any biological variance and their magnitudes are determined by the arbitrarily chosen combining functions.

*Karr deserves great credit for demonstrating and selling the idea that biological survey data and regional reference communities can be used in environmental regulation. This paper does not attack that concept but rather the much more limited belief that the best way to use the biosurvey data is to create an index of heterogeneous variables and claim that it represents ecosystem health.

Unreality

Indexes of heterogeneous variables are not measures of any real-world property. They have nonsense units. That is an inherently undesirable property, but it also implies that the results of environmental studies, when expressed as indexes of heterogeneous variables, cannot be valued by a decision maker or balanced against other values. Is a 0.8 unit reduction in an ecosystem health index important enough to spend a million dollars on remediation, 10 million dollars, . . . ? Is it better to use limited funds to remediate a wetland with a wetland health index of 5 or a stream with a stream health index of 3? Is it better to remediate a stream with an IBI of 8 an HI of 4 or one with an HI of 8 and an IBI of 4?

The fact that two indexes as dissimilar as the IBI and HI can be said with equal legitimacy to be measures of ecosystem health indicates that ecosystem health (or any other property that can be defined only by indexes of heterogeneous variables) is nothing in particular. Only real properties have real value. Use of unreal properties (particularly unreal properties with imposing names) in environmental regulation obscures the bases for decision making; increases the opportunity for arbitrariness; and decreases the opportunity for informed input by the public, regulated parties, or advocacy groups.

Finally, use of an unreal property as an operational goal puts environmental management outside the particular preview of science. The unique power of science is a result of its ability to develop predictive theories that are confirmed by systematic observation of real-world phenomena. An artist or theologian could provide a method for defining ecosystem health based on color or scriptural prophesy, and neither the HI nor the IBI could be proven better. In contrast, a scientific theory such as dose response or habitat suitability could be shown to better predict a real-world property such as the presence of trout in a stream following a defined perturbation.

Post hoc justification

Indexes like the IBI, but not HI, are justified on the basis of field studies rather than any theory of ecosystem health or any societal or ecological value of the index or its components. That is, an ecosystem's health is bad because the index is low, and a low index value indicates bad health because the index is low for unhealthy ecosystems. Logically, this is a tautology. This commonsensical but logically impermissible approach will work only so long as all ecosystems in all cases become unhealthy in the same way.

Unitary response scale

Combining heterogeneous measures into a single index implies that there is only a single linear scale of response and therefore only one type of response by ecosystems to disturbance. It implies that there is only one mode of action. For example, measurement of 12 component responses implies that an ecosystem can respond to disturbance by moving on any vector in a 12-dimensional state space, but combining those variables into a single index implies that only one vector is possible. That is, all ecosystems in response to all perturbations become unhealthy in the same way.

No diagnostic results

One of the most important uses of biological survey data is to determine the cause of changes in ecosystem properties. The best way to do this is to examine the types of responses for characteristic symptoms of specific agents and the relative magnitudes of responses of the various components relative to their known sensitivity to the agents. Combining responses into an index hides the component responses, thereby obscuring causation. More important, choosing parameters as components of a generic ecosystem health index that is designed to respond equivalently to all disturbances would result in a different parameter set than choosing parameters that are diagnostic of different classes of disturbances.

Disconnected from testing and modeling

Indexes of ecosystem health cannot be tested in the laboratory. Proving that a correlation in the field (e.g., between an index value and concentration of a chemical pollutant) is due to a particular causal factor requires that the association be verified in controlled studies (e.g., toxicity tests). No toxicity test generates an IBI or HI and no model estimates IBI or HI from any set of toxicity test data.

Nonsense results

Any index of heterogeneous variables can produce nonsense results, and the nonsense is obscured because the index has no real-world meaning that can be interpreted. For example, the HI of Lake Tahoe is rising because its productivity and metabolism are increasing and because, as lakes move from an oligotrophic to a mesotrophic state, their organization (diversity) increases. Although it might be argued that mesotrophic lakes are healthier than oligotrophic lakes like Tahoe (R. Costanza, personal communication), few people would argue that the loss of clarity and other changes wrought by anthropogenic nutrient input to Lake Tahoe are desirable. Similarly, the IBI goes down as the abundance of green sunfish and other designated tolerant species goes up. However, green sunfish are not tolerant of all chemicals and may actually be more sensitive than the "intolerant" species to some classes of chemicals in the field [18] and laboratory [19]. Reductions of emissions of any of the chemicals to which green sunfish are sensitive would lower the IBI, implying that the system had become less healthy. If one said "the productivity of the lake is increasing" or "the green sunfish population is recovering," the meaning would be clear, but saying "the HI is increasing" or "the IBI is declining" would be misleading.

Improper analogy to other indexes

Advocates of environmental indexes often argue that, because economic indexes have been used successfully to represent complex economic systems, environmental indexes should be equally useful. However, Ott [17] pointed out that the analogy of environmental to economic indexes is misleading. Rather than attempting to represent something as broad and undefinable as economic health, economic indexes are relatively simple combinations of factors, are expressed in common monetary units, and are readily comprehensible to decision makers and the public. In contrast, environmental indexes are combinations of diverse components and are not generally comprehensible. Their use in decision making requires an act of faith rather than informed judgment.

ALTERNATIVE CONCEPTS AND METRICS

Alternative metrics

Health is not a property of ecosystems, health is not a quantitative or qualitative scalar property of humans in either medicine or risk assessment, and the indexes used to quantify ecosystem health have several undesirable properties as bases for decision making. If, as Karr [20] suggests, the only alternative to regulation on the basis of ecosystem health indexes is regulation on the basis of chemical concentrations or best available technologies, then even those faults might be ignored. However, there are alternative ways to use the results of field biological data in environmental regulation.

First, one can examine the real, measurable properties of ecosystems and choose a set that are worthy of protection. (In the jargon of risk assessment, one would choose measurement end points that correspond to assessment end points or are well correlated with assessment end points [21].) Because each of the chosen properties would be deemed to be important, significant damage to any one could be a sufficient basis for action. The sets of properties would differ among classes of ecosystems and could differ among decisions.

Second, one could measure a set of properties that could be used to estimate a higher level property that was an assessment end point. For example, one could measure properties of fish and use a conceptual or quantitative model to estimate properties of fish populations [22–23], which would be similar to the development of air-quality indexes. Having identified a high-level response (frequency or human eye or respiratory irritation) that was a function of several parameters (concentrations of pollutant gases), one could devise an index that weighted and combined those parameters so that the response was a linear function of the index. Note that in this case, unlike the ecosystem health indexes, the index predicts the response of a real property of the system (irritation), and the components of the index are not heterogeneous; they are all concentrations of air pollutants.

Third, if one wishes to use a set of heterogeneous measures to characterize an ecosystem relative to other ecosystems of the same type, there are statistical techniques that provide an alternative to simply adding or multiplying the results to create an index. One is state space analysis, which describes the location of the system of interest as a point in a Cartesian space with n dimensions corresponding to the n properties measured. If multiple measures are taken over time or space, then the system is defined as a vector or a cloud of points in the n space. One can estimate the likelihood (risk) that a disturbed system belongs to a different state space from a set of nominally undisturbed reference systems [24]. Alternatively, one can calculate the deviation of a disturbed system from the reference systems relative to the variance of the reference systems in the chosen state space [25]. Other techniques from descriptive statistics, including principal component analysis and similarity indexes, are also potentially useful [26–28]. They have the advantages over indexes of (a) retaining the identity of the individual, measured properties and showing which account for most of the differences among systems; (b) having nonarbitrary statistical and mathematical properties; and (c) not purporting to represent a property of the system (they simply show how the systems differ rather than claiming to be a measure of health, integrity, etc.).

Some reviewers of this paper have responded to point (a) by saying that the component variables can be carried along with the index, but in that case there is no advantage to calculating the index. If the decision maker must consider all component variables as well as the index, and the index does not illuminate relationships among the variables as a multivariate statistical analysis would, then nothing is gained. One appeal of ecosystem health indexes is that they save the decision maker from confronting the real complexity of ecosystems and deciding what is important. In contrast, it is hard to imagine that a decision maker would interpret the first principal component as an adequate sole basis for regulatory action.

Alternative goals

Before considering which alternative terms might better serve to designate the overall goal of environmental management, it is necessary to consider the function of such terms. Ecosystem health has been used as an operational goal although it can be defined only in terms of indexes of heterogeneous variables or equivalent inventions. This is in part because environmental managers have been reluctant to define their goals clearly, so they have embraced ecosystem health in the belief that health is an operational term for physicians that can be adopted metaphorically. This is not the case in economics, which has its own clearly and operationally defined goals and which uses the phrase "economic health" simply to designate those goals as a set. Environmental managers need to step back, establish clear and operationally definable goals, then choose a term or phrase to designate that set of goals. That term should not be burdened with misleading metaphorical baggage (although it could be metaphorical) or with meaningless indexes that substitute for real-world properties.

"Sustainability" or "quality" are preferable to "health" as expressions of the abstract property that encompasses the specific goals of environmental management. First, they do not imply a false ecosystem paradigm. Paradigms and the metaphors on which they are based make a difference in the success of a science [9]. In particular, the ecosystem health metaphor creates the illusion that there is a property of ecosystems equivalent to human health that can be ascertained and protected. It seems to save people from the difficult task of judging the quality of value of alternate states of ecosystems. In other words, quality and sustainability are simply broad goals, but the health metaphor also implies an operational property. Although it might be desirable to have a paradigm for ecosystems, and that paradigm could be based on a metaphor, there is currently no acceptable ecosystem paradigm [9,11,29]. In the absence of a useful paradigm or metaphor, we must attempt "to observe nature as it is, not as we imagine it to be" [9].

The alternative terms *quality* and *sustainability* do not raise misleading expectations by analogy to a very different science. Just as ecology, after decades of frustration, had to abandon its attempt to develop laws equivalent to the laws of physics, the applied environmental sciences will have to develop their own concepts, techniques, and standards of success rather than raising expectation of ecosystem medicine.

Use of the term *sustainability* implicitly raises the questions "Which environmental properties must be sustained?" and "Which human uses of the environment must be sustained?" Whereas the use of "ecosystem health" raises expectations that all ecosystems can be maintained in or restored to a healthy state equivalent to an idealized pre-Columbian condition, "sustainability" implies a recognition of the inevitability of human–environment interaction. It is a more mature and realistic goal for environmental regulation and management. These and other considerations led the Ecological Society of America to develop a Sustainable Biosphere Initiative [30]. Quality is a more traditional goal than sustainability (it is a goal of the U.S. National Environmental Policy Act). It does not define the issues as clearly as sustainability, but it is broader and likely to be acceptable to those who find the concept of sustainability too utilitarian.

Either goal avoids the impression that environmental managers are like medical doctors responding to the complaints of a patient or like health risk assessors calculating the number of cancer deaths. Rather, environmental managers are active agents, translating the inchoate norms of the current generation and the poorly predicted needs of future generations into specific actions to protect or restore real, valued properties of actual ecosystems. This difficult enterprise can succeed only by developing clarity of purpose in place of a vague longing to imitate other professional fields. Clarity of purpose would also eliminate the need for meaningless index values as expressions of undefined regulatory goals. Hence, the decision to abandon ecosystem health as a goal is *not* just a matter of semantics.

It is part of the development of a mature, confident, and useful science and practice of environmental management

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