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# On the study of ecosystem health: state of the art

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**Abstract**: Ecosystem health is a newly proposed concept that sets new goals for environmental management. Its definition, assessment indicators, and assessment methods are reviewed in this paper. Literature shows that the definitions and the assessment indicators cover a wide range of ecosystem health, and they differ in terms of researchers' different scientific background. It is concluded that the concept of ecosystem health cannot be defined or understood simply in biological or ethical or aesthetic or historical terms and the assessment should be based on applying several indicators simultaneously to get overall picture of the health or integrity state of an ecosystem.

**Key words**: ecosystem health; environmental management; ecological indicators

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## Introduction

During last decades, the term "ecosystem health" is used with increasing frequency in the literature. The growing interests in the studies on ecosystem health has resulted in establishment of international specialized societies (e. g. International Aquatic Ecosystem Health and Management Society (IAEHMS) and International Ecosystem Health Society (IEHS)), and publication of international scientific journals (e. g., Aquatic Ecosystem Health, and Ecosystem Health). More and more environmental managers consider the protection of ecosystem health as new goals of environmental management. However, owing to the complexity of ecosystems, it is not an easy task to provide an operational definition, and to find proper indicators for measuring ecosystem health, although many ecologists and system ecologists have been working on these issues.

## 1 The definitions of ecosystem health

Karr *et al*. (Karr, 1986) presented a definition of ecosystem health. That is "a biological system, whether individual or ecological, can be considered healthy when its inherent potential is realized, its condition is stable, its capacity for self-repair when perturbed is preserved, and minimal external support for management is needed".

Schaeffer *et al*. (Schaeffer, 1988) suggested that "health should not depend on criteria based in the presence, absence, or condition of a single species, and on a census or even inventory of large numbers of species; and that health should reflect our knowledge of normal succession or expected sequential changes that occur naturally in ecosystems".

Rapport (Rapport, 1989) noted that the concept of ecosystem health could be derived by analogy with concepts of human health; and he even used the phrases "to take nature's plus", "the problem of detecting diseases in nature" and "clinical ecology" to stress the parallelism to human pathology. He pointed out that a health ecosystem exhibits certain fundamental properties of self-organizing complex systems, including Bertalanffy' (Bertalanffy, 1950) four major attributes of complex system evolution, "progressive integration", "progressive differentiation", "progressive mechanization", and "progressive centralization".

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Norton (Norton, 1991) suggested a framework for defining ecosystem health, including the axiom of dynamism, relatedness, hierarchy, creativity, and differential fragility.

Haskell *et al*. (Haskell, 1992) concluded: "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".

Page (Page, 1992) considered health as "a harmonious relationship among the parts of the body and between the body and the outside world; and the concept of homeostasis, taught in medical schools as a normative concept, has a direct parallel with the notion of stability in ecosystems".

Ulanowicz (Ulanowicz, 1992) proposed that "a healthy ecosystem is one whose trajectory toward the climax is relatively unimpeded and whose configuration is homeostatic to influences that would displace it back to earlier succession stages".

Some ecologists prefer to use the term "ecological (or biological) integrity" instead of "ecological health" (Kay, 1991; Karr, 1992). In long-range policy documents in the United States, "ecological integrity" and "ecological health" are used ubiquitously as goals of protection efforts (Haskell, 1992). Karr (Karr, 1992) pointed out that "health and integrity have multiple meanings, and that "health" may be used in a human context (the condition of being sound in body and mind or spirit; freedom from physical disease or pain) or an economic context (a flourishing condition, such as the economic health of a country); 'integrity' implies an unimpaired condition or the quality or state of being complete or undivided".

There are some other approaches to define ecosystem health from philosophers, physical scientists, and managers (Costanza, 1992). Costanza point out that all of above concepts represent pieces of the puzzle, but none is comprehensive enough to serve as an operational definition. He summarized the concept definition of ecosystem health as follows: (1) health as homeostasis; (2) health as the absence of disease; (3) health as diversity or complexity; (4) health as stability or resilience; (5) health as vigor or scope for growth; and (6) health as balance between system components. He emphasized that an adequate definition of ecosystem health should integrate the concepts of health mentioned above, i. e. it should be a combined measure of system resilience, balance, organization (diversity), and vigor (metabolism). It can be seen from this concept definition that a healthy ecosystem must maintain its metabolic activity level as well as its internal structure and organization, and must be resilient to outside stresses over a time and apace frame relevant to that ecosystem.

## 2 Ecosystem health assessment indicators

Several ecological indicators have been proposed to characterize the development state and the changes of ecosystems under external perturbations, e. g. maximum power (Odum, 1960), diversity (Margalef, 1961), biomass (Straskraba, 1980), emergy (Odum, 1982), exergy (Jφgensen, 1982), ascendency (Ulanowicz, 1986), and entropy (Schneider, 1988). Ecological indicators are used increasingly to assess the environmental impacts of various contamination and the "health" condition of ecosystems. Historically, the health of an ecosystem has been measured using indices of a particular species or components. Toxicologists recognize the importance of individual health in evaluating the extent to which human actions have degraded ecological health. Ecologists measure species richness or the relative abundance of species to evaluate ecological conditions. Fish biologists use measures of population age structure to assess the health or vitality of target populations. Such indices are inadequate because they are not broad enough to reflect the complex of ecosystems. From a managerial or political standpoint, however, these single species indices are some useful in communicating complex information to resource managers, politicians, and the public ecosystem (Haskell, 1991). New indices have been developed that better reflect the complexity of the ecosystem and are being used for management purposes.

Karr (Karr, 1981; 1986) developed the Index of Biotic Integrity (IBI) as an approach, now widely used in North America and in Europe, to the assessment of the quality of water resources. Most of the components of the original IBI were well-known associations between system condition and human influence. Using the connection of a biological vector, IBI is an integration of twelve attributes of segment of the biota (fish) of a stream.

Hannon (Hannon, 1985) proposed the gross ecosystem product (GEP) which is analogous to the GNP as an ecological indicator for the measures of two tidal marsh ecosystem health.

Rapport *et al*. (Rapport, 1985) reviewed some stresses and their symptoms, and gave five indicators of ecosystem stress: nutrient pool, primary productivity, size distribution, species diversity, and system restogression (toward early stages). A variety of indicators are running the gamut from early warning signs of ecosystem dysfunction to indicators that confirm the presence of significant ecosystem pathology. He noted that, in general, such system-wide indicators appear late in the breakdown process and that species-directed fieldwork is needed to provide early warning.

Ulanowicz (Ulanowicz, 1980; 1986) developed the index of network ascendency which incorporates four important characteristics of ecosystems: species richness, niche specialization, developed cycling and feedback, and overall activity. The network ascendency is the product of two factors, one that gauges the level of system activity, and another that captures the degree of trophic organization. Ulanowicz (Ulanowicz, 1992) suggested to use this index to assess ecosystem health.

Kay *et al*. (Kay, 1991) emphasized that the measures of ecosystem health or integrity should reflect two aspects of the organization state of an ecosystem: functional and structural. Function refers to the overall activities of the ecosystem; and structure refers to the interconnection between the components of the system. Measures of function would indicate the amount of energy being captured by the ecosystem; and it could be covered by measuring the exergy captured by the system. Measures of structure would indicate the way in which energy is moving though the system; and the exergy stored in the ecosystem could be a reasonable indicator of the structure. They applied a set of ecosystem indicators, including biomass imports, exports, production, respiration, cycles, nexuses, Finn cycling index, and ascendency for the assessment of the Crystal River March Gut Ecosystem health or integrity.

On the base of summarizing definition of ecosystem health, Costanza (Costanza, 1992) proposed an overall system health index, $HI = V \times O \times R$, where V is the system vigor, a cardinal measure of system activity, metabolism, or primary productivity; O is the system organization index, a 0—1 index of relative degree of the system organization, including its diversity and connectivity; and R is the resilience index, a 0—1 index of relative degree of the system resilience. Costanza touches probably with this proposal on the most crucial ecosystem properties to cover ecosystem health.

Jφrgensen (Jφrgensen, 1995) introduced exergy, structural exergy and ecological buffer capacities as ecological indicators for the measures of ecosystem health. He pointed out that exergy as an ecosystem health indicator can cover points (1) homeostasis; (2) absence of disease, partly; (3) diversity or complexity; (4) stability or resilience; (5) vigor or scope for growth of Constanza's concept definition of ecosystem health. Structural exergy as an ecosystem health indicators can cover biodiversity (point 3) and balance between system components (point 6) and trophic state. Ecological buffer capacity as an ecosystem health indicator can give good description of stability or resilience (point 4) of Constanza concept definition of ecosystem health, since it is based on reality that an ecosystem will never exactly return to the same situation again. The relation between forcing functions and state variables are rarely linear and ecological buffer capacities are not constant. Therefore, ecological buffer capacity seems to the most applicable stability concept, and it is a multi-dimensional concept, since all the combinations of state variables and forcing functions may be considered. He emphasized that these three concepts can combine the Costanza's definition and the three components in Costanza index.

Dalsgaard (Dalsgaard, 1995; 1996) applied a series of ecological indicators, including biomass (B), harvest (H), N throughput (E), system overhead, P/B, H/E, efficiency, Shinn index, Finn cycling index, ascendency, exergy, structural exergy, and buffer capacities to the quantitative comparisons of maturity or sustainability of four agroecosystems with different complexity.

Xu (Xu, 1996) used diversity index (DI), trophic state index (TSI), exergy (Ex), structural exergy ($Ex_{st}$), and phytoplankton buffer capacity $\delta_{(TP)(phyto)}$ as ecological indicators for the ecosystem health assessment of Lake Chao, a shallow eutrophic lake in China. On the base of the investigation on the structural, functional, and system-level responses of freshwater ecosystem to four chemical stress (acidification, oil, copper, and organic chemical contamination), Xu (Xu, 1997; 1999) suggested a set of comprehensive ecological indicators including structural, functional, and system-level indicators. Structural indicators include phytoplankton cell size and biomass, zooplankton body size and biomass, macro- and micro-zooplankton biomass, the zooplankton/phytoplankton ratio, macrozooplankton/microzooplankton ratio, and species diversity. Relative to contaminated ecosystems, a healthy ecosystem will have the following structural characteristics: small cell size phytoplankton, large body size zooplankton, high zooplankton and macrozooplankton biomass, low phytoplankton and microzooplankton biomass, high zooplankton/phytoplankton ratio, high macrozooplankton /microzooplankton ratio, and high species diversity.

Functional indicators include algal C assimilation ratio, resource use efficiency, community production, $P/R$ ratio, $P/B$ ratio, and $B/E$ ratio. The food web function of a healthy ecosystem shows high algal C assimilation, high resource use efficiency, low community production, high $P/B$ and $B/E$ ratio, and $P/R$ ratio approaching 1. Ecosystem-level indicators include exergy, structural exergy, and ecological buffer capacities. Generally, high exergy, high structural exergy, and high buffer capacities imply good health. If the exergy and structural exergy is high, but one of the focal buffer capacities is low, the ecosystem structure is unbalance. If the exergy is high but the structural exergy and some focal buffer capacities are low, the ecosystem is probably an eutrophic system.

Plainly, it is not an easy task to find good ecological indicators to assess ecosystem health. A number of researchers have proposed different indicators that cover different aspects of ecosystem health. Ecologists are still centered on the idea of an empirical set of ecosystem indicators (Hannon, 1992). Anyhow, it may be necessary to apply several indicators simultaneously to get a sufficient image of the health or integrity of an ecosystem (Jφrgensen, 1997), since the domain of ecosystem health is vast, and it encompasses not only biophysical dimension, but also socio-economic and human aspects (Karr, 1992; Rapport, 1992a; 1995). Only a multi-view description can capture all the features needed to give a fully informative assessment of the condition of an ecosystem (Jφrgensen, 1997).

## 3 The procedure for ecosystem health assessment

There is no uniform procedure for ecosystem health assessment. Some approaches have been proposed.

Schaeffer *et al*. (Schaeffer, 1988) suggested some guidelines to follow: (1) ecosystem health does not have to be measured as a single number, and single numbers compress a large number of dimensions (one for each type of item); (2) health measures should have a defined range; (3)

health criteria should be responsive to change in data values but should not show discontinuities even when values change over several decades; (4) health measures should have known statistical properties, if these are relevant; (5) criteria for health assessment must be related and hierarchically appropriate for use in ecosystems; (6) health measures should be dimensionless or share a common dimension; (7) health measures should be insensitive to the number of observations, given some minimum number of observations.

Haskell *et al*. (Haskell, 1992) proposed to use the practice of human and animal medicine as model for the practice of ecological medicine. The assessment of health in medicine follows this sequence: (1) identify symptoms; (2) identify and measure vital signs; (3) make a provisional diagnosis; (4) conduct tests to verify the diagnosis; (5) make a prognosis; (6) prescribe a treatment. This model of health assessment is applicable to ecosystem, but ecologists do not have their disposal a compendium of known disease or stress with associated symptoms and signs. Although it is therefore impossible to make an accurate diagnosis and prescribe the appropriate treatment for an ailing ecosystem, ecologists have nevertheless started to categorize certain stresses and record their effects (symptoms) on the ecosystem (Rapport, 1985).

Jφrgensen (Jφrgensen, 1995) proposed a tentative procedure for a practical assessment of ecosystem health, based on models and ecological indicators (exergy, structural exergy, and buffer capacities): (1) set up the relevant question related to health of a considered ecosystem; (2) assess the most important mass flows and mass balances related to these questions; (3) make a conceptual diagram of the ecosystem, containing the components of importance for the mass flows defined under 2; (4) develop a dynamic model (if the data are not sufficient, a steady state model should be applied) using the usually procedure ( Jφrgensen, 1994); (5) calculate exergy, structural exergy, and relevant buffer capacities by the use of the model, in addition if the model is dynamic it will be possible to find also the seasonal changes in exergy, structural exergy, and buffer capacities; (6) assess the ecosystem health: high exergy, structural exergy, and buffer capacities imply a good ecosystem health.

Xu (Xu, 1996; 1997) proposed a procedure which can be regard as a modification of Jφrgensen procedure (Jφrgensen, 1995): (1) analysis and determine the important components (forcing functions and state variables) in the lake ecosystem; (2) make the measurements of important components; (3) calculate the values of ecological indicators, e.g. trophic state index (TSI), diversity index (DI), exergy (Ex), structural exergy ($Ex_{st}$), and phytoplankton buffer capacity ($\delta_{(TP)(phyto)}$) by use of the measured data; and (4) assess ecosystem health: low trophic state index, high diversity index, high exergy, high structural exergy, and high buffer capacities imply good health.

## 4 Conclusion

The definition, assessment indicators, and assessment methods of ecosystem health have been reviewed. There are many different definitions and assessment indicators which proposed by various researchers including philosophers, economists, ecologists, and managers. These definitions and indicators cover a wide range of aspects of ecosystem health. Clearly, the concept of ecosystem health cannot be defined or understood simply in biological or ethical or aesthetic or historical terms. It is necessary to apply several indicators simultaneously to get overall picture of the health or integrity state of an ecosystem.

## References:

Costanza R, 1992. Ecosystem health: new goals for environmental management [M] (Eds. by Norton B G, Haskell B D). Island

Press Washington D. C., Covelo.
Dalsgaard J P T, 1995. NAGA, The ICLARM Quarterly [J], 18(2):15—19.
Dalsgaard J P T, Lightfoot C, Christensen V, 1995. Ecological Engineering [J], 4: 181—189.
Dalsgaard J P T, 1996. An ecological modelling approach towards the determination of sustainability in farming system [D]. Royal Agriculture & Veterinary. University.
Haskell B D, Norton B G, Costanza R, 1992. Ecosystem health: new goals for environmental management [M]. 3—20.
Jφrgensen S E, Mejer H, 1997. Ecol Model [J], 3:39—61.
Jφrgensen S E, Mejer H F, 1979. Ecol Model [J], 7:169—189.
Jφrgensen S E, 1982. Energetics and systems [M] (Eds. by Mitsch W, Ragade R, Bosserman R, Dillon J ). Ann Arbor, MI: Ann Arbor Science Publishers. 61—72.
Jφrgensen S E, 1992a. Integration of ecosystem theories: A pattern [M]. Dordrecht/Boston/London: Kluwer Academic Publishers.
Jφrgensen S E, 1994a. VIE MILIEU [J], 44(1):11—20.
Jφrgensen S E, 1994b. Fundamentals of ecological modelling [M](second edition). Amsterdam: Elsevier. 630.
Jφrgensen S E, 1995a. Ecosystem Health [J], 1(3):150—160.
Jφrgensen S E, 1995b. Lakes & Reservoirs: Research and Management [J], 1: 177—182.
Jφrgensen S E, 1997. Integration of ecosystem theories: a pattern [M]. Kluwer Dordrecht. 400.
Karr J R, 1981. Fisheries [J], 6:21—27.
Karr J R, 1992. Ecosystem health: new goals for environmental management [M] (Eds. by Costanza R, Norton B G, Haskell B D). Island Press Washington D. C., Covelo. 223—238.
Karr, J R, Fausch K D, Angermeier P L *et al*., 1986. Assessing biological integrity in running waters: a method and its rational [M]. Champaign: Illinois Natural History Survey, Special Publication 5.
Kay J J, Schneider E D, 1991. Ecological indicators[M](Ed. by McKenzie D). Amsterdam. 159—182.
Margalef R, 1961. Limnol Oceanogr [J], 6:124—128.
Norton B C, 1992. Ecosystem Health: new goals for environmental management [M] (Eds. by Costanza R, Norton B G, Haskell B D). Island Press Washington D. C., Covelo. 23—41.
Odum H T, 1960. Am Sci [J], 48:1—8.
Odum H T, 1982. Energetics and systems [M] (Eds. by Mitsch W, Ragade R, Bosserman R, Dillon J). Ann Arbor MI: Ann Arbor Science. 33—66.
Page T, 1992. Ecosystem health: new goals for environmental management [M] (Eds by Costanza R, Norton B G, Haskell B D). Island Press Washington D C, Covelo. 97—123.
Rapport D J, Regier H A, Hutchinson T C, 1985. American Naturakist [J], 125: 617—640.
Rapport D J, 1989. Perspectives in Bio And Med [J], 33: 120—132.
Rapport D J, 1992a. Ecosystem health: new goals for environmental management [M] (Eds. by Costanza R, Norton B G, Haskell B D). Island Press Washington D. C., Covelo. 144—156.
Rapport D J, 1992b. Ecological indicators [M] (Eds. by Mckenzie D H, Hyatt D E, Mcdonald V J). London, New York: Elsevier Applied Science. 121—134.
Rapport D J, 1995. Ecosystem Health [J], 1(1):5—13.
Schneider E, 1988. Entropy, information and environment, a bradford book [Z] (Eds by Weber B H, Depew D J, Smith J D).
Schaeffer D J, Herricks E E, Kerster H W, 1988. Environmental Management [J], 12: 445—455.
Straskraba M, 1980. ISEM J [J], 2:81—96.
Ulanowicz R E, 1980. Journal of Theoretical Biology [J], 85:223—245.
Ulanowicz R E, 1986. Growth and development: ecosystems phenomenology [M]. New York: Springer-Verlag.
Ulanowicz R E, 1992. Ecosystem health: New goals for environmental management [M](Eds. by Costanza R, Norton B G, Haskell B D). Island Press Washington D. C., Covelo. 190—206.
Xu F L, 1996. Lakes & Reservoirs: research and management [J], 2: 101—109.
Xu F L, 1997. Modelling the effects of ecological engineering on ecosystem health of the Lake Chao, a eutrophic Chinese lake [D].
Xu F L, Jφrgensen S E, Tao S, 1999. Ecological Modelling[J], 119:77—106.

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