

Ecosystem health towards sustainability

Yonglong Lu,^{1,5} Ruoshi Wang,^{1,2} Yueqing Zhang,^{1,2} Hongqiao Su,^{1,2} Pei Wang,^{1,2} Alan Jenkins,³ Rober C. Ferrier,⁴ Mark Bailey,³ and Geoff Squire⁴

¹State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085 China

²University of Chinese Academy of Sciences, Beijing 100049 China

³Centre for Ecology and Hydrology, Wallingford OX10 8BB United Kingdom

⁴James Hutton Institute, Aberdeen AB15 8QH Scotland, United Kingdom

Abstract. Ecosystems are becoming damaged or degraded as a result of stresses especially associated with human activities. A healthy ecosystem is essential to provide the services that humans and the natural environment require and has tremendous social and economic value. Exploration of the definition of ecosystem health includes what constitutes health and what it means to be healthy. To evaluate ecosystem health, it is necessary to quantify ecosystem conditions using a variety of indicators. In this paper, the main principles and criteria for indicator selection, classification of indicators for different kinds of ecosystems, the most appropriate indicators for measuring ecosystem sustainability, and various methods and models for the assessment of ecosystem health are presented. Drivers, sustainability, and resilience are considered to be critical factors for ecosystem health and its assessment. Effective integration of ecological understanding with socioeconomic, biophysical, biogeochemical, and public-policy dimensions is still the primary challenge in this field, and devising workable strategies to achieve and maintain ecosystem health is a key future challenge.

Key words: *assessment methodology; ecological indicator; ecosystem functioning; ecosystem health; ecosystem sustainability; resilience.*

Citation: Lu, Y., R. Wang, Y. Zhang, H. Su, P. Wang, A. Jenkins, R. C. Ferrier, M. Bailey, and G. Squire. 2015. Ecosystem health towards sustainability. *Ecosystem Health and Sustainability* 1(1):2. <http://dx.doi.org/10.1890/EHS14-0013.1>

Definition of Ecosystem Health

Human activity is considered to be the major driver of global environmental change and has great impacts on the Earth system (Vitousek et al. 1997). Climate change (Moss et al. 2010), land use change (Foley et al. 2005), biodiversity loss (Butchart et al. 2010), and many other environmental issues highlight the tremendous effect of human activity in our increasingly demanding economic world. Climate change, including temperature and precipitation change, has affected the phenology of organisms, the range and distribution of species, and the composition and dynamics of plant communities. (Walther et al. 2002, Parmesan and Yohe 2003, Root et al. 2003). Climate change has impacts on crop productivity and has consequences for food availability (Godfray et al. 2010, Wheeler and von Braun 2013). Land use change, especially the expansion of croplands, pastures, plantations, and urban areas to meet human needs, has resulted in considerable losses of biodiversity (Foley et

al. 2005). Such decreases of biodiversity may reduce ecosystem services that are vital to agriculture, such as pollination (Tscharntke et al. 2005). Habitat destruction also results in loss of ecosystem services and species extinctions (Tilman et al. 2001). As well as direct damage, the resilience of ecosystems and the functions they maintain are compromised through direct and indirect impacts of humans and environmental stress.

Development of ecosystem health concept

Since the Stockholm Conference on Human Environment held in 1972, ecologists have paid close attention to the study of how natural ecosystems respond to the various kinds of stresses from human activity. In order to measure ecosystem response to stress, Rapport et al. (1985) followed the physiologist, the late Hans Selye (1973, 1974), who provided a framework for stress physiology by identifying common symptoms and the phases of adaptation to stress in mammalian systems. Health here refers to the absence of symptoms of ecosystem dysfunction based on a group of indicators and using subjective judgment rather than scientific criteria. This is the rudiment of ecosystem health:

Manuscript received 3 September 2014; revised 28 October 2014; accepted 2 December 2014.

⁵ E-mail: yllu@rcees.ac.cn

physiological methods have been creatively imported into the study of ecology.

What constitutes “health” reflects the perspective through which we evaluate ecosystems and the indicators we use to assess them. Schaeffer et al. (1988) defined ecosystem health as the absence of disease, and disease here was defined as the failure of the ecosystem to function within acceptable limits, thereby leading to an inadequate homeostatic repair mechanism. Rapport (1989) defined ecosystem health from three perspectives: vital signs and system integrity, counteractive capacity, and threats from stress on the environment that are influenced by social and cultural values. Costanza (1992) proposed that “ecosystem health is closely linked to the idea of sustainability, which is seen to be a comprehensive, multi-scale, dynamic measure of system resilience, organization, and vigor.” What is “healthy” involves the direction and magnitude of deviation from normal status. Mageau et al. (1995) suggested that a healthy ecosystem is one that is sustainable; that is, it has the ability to maintain its structure and function over time in the face of external stress.

Ecosystem health was discussed at international conferences at the beginning of the 1990s (Costanza et al. 1992), and a “working definition” of ecosystem health was presented in terms of characteristics for sustainability, which is a function of activity, organization, and resilience. It was concluded that “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” (Haskell et al. 1992). Previous definitions had been given in terms of organization, resilience and vigor. Rapport et al. (1998) suggested combining these three elements into a biophysical perspective and incorporating socioeconomic and human health perspectives. Different from the previous concepts concerned with natural ecosystems, this construct has been widely applied in human-coupled ecosystems.

Criticisms of the concept of ecosystem health and its theoretical basis were further explored in the 1990s. An early criticism focused on the organism theory—the idea that ecosystems are structurally and functionally like organisms. Ehrenfeld (1992) and Suter (1993) argued that ecosystems are not organisms, per se, so they do not have properties of organisms such as health. Another controversy over ecosystem health is whether it is an objective scientific concept. Using the term “health” to describe an ecosystem implies there is a state that is good or bad for the system. However, the assessment of good or bad states of ecosystems can only be based on the kind of ecosystem expected by society (Wicklum and Davies 1995). Ecosystem health is therefore a term of value judgment. Value judgment changes over time as our understanding of the natural world changes, so it is not appropriate as a scientific basis for managing the environment (Lancaster 2000).

However, as Costanza (2012) argued, ecosystem health is a “normative” concept that implies specific societal goals, rather than an “objective” scientific concept. Homeostasis might not be a common property of organisms and ecosystems, but that is not a reason for discarding ecosystem health as a useful concept. Moreover, the normative terms are mostly institutionalized in national and international policy and law (Callicott et al. 1999). For example, ecosystem health is used in the *Rio Declaration on Environment and Development* for setting up a global agenda for ecosystem management (UN General Assembly 1992).

Ecosystem health and ecosystem services for sustainability

Ecosystem health is essential for an ecosystem to provide services that benefit the human population in terms of social and economic value. Ecosystem services are generally divided into four categories: provisioning, regulating, supporting, and cultural services (Costanza et al. 1997, Millennium Ecosystem Assessment 2005). Supply of services relies on a well-conditioned ecosystem, and the capacity of service supply will be impaired if an ecosystem is unhealthy, for example through loss of biodiversity (Balvanera et al. 2006, Worm et al. 2006). In order to advance human welfare through improved ecosystem services, a better understanding of the integrated social-ecological system is needed so that appropriate policies and practices can be formulated (Carpenter et al. 2009). Moreover, advances are required in the design of appropriate finance, policy, and governance systems and the form of implementation in diverse social and ecological contexts (Daily and Matson 2008). Ecosystem services have been put into implementation in environmental management in many countries. For example, in China, the national programs of payments for ecosystem services such as the Natural Forest Conservation Program (NFCP) and the Grain to Green Program (GTGP) have improved ecosystem conditions and produced positive social-economic effects (Liu et al. 2008). In the UK, the National Ecosystem Assessment (2011) increasingly provides a basis for advocating change to more sustainable states.

After a couple of decades of discussion, the concept of ecosystem health has been gradually accepted and applied in the world. However, the “standard” of health as a concept is influenced by value judgment and is not completely objective, but ecosystem health is proving to be a normative and useful concept in environmental management. Structural organization and vigor need to be considered in order to reflect ecosystem structure and function, and resilience is critical in reflecting the capacity to recover from a perturbation. Concurrently, social-economic aspects are fundamental to assessment, especially when evaluating trade-offs between ecosystem services, for example when comparing provisioning

and supporting functions. Ecosystem health is closely related to the concept of sustainability, which is defined to meet the current and future societal need for ecosystem services. The potential to continuously supply ecosystem services for the coming generations has been highlighted as an important issue within environment justice.

Based on this discussion, we define ecosystem health as the status and potential of an ecosystem to maintain its organizational structure, its vigor of function and resilience under stress, and to continuously provide quality ecosystem services for present and future generations in perpetuity.

Indicator System for Ecosystem Health

Criteria for indicator selection

Main principles

To evaluate ecosystem health, either qualitative or quantitative analysis needs to be made using a variety of indicators. Ideally, the suite of indicators should represent key information on the ecosystem structure and function and be specific for the goal of the assessment. In this regard, the following principles may be used for selection of key indicators.

1. Assess integrative ecosystem health.—Costanza (1992) and Rapport et al. (1998) proposed three groups of indicators, vigor, organization, and resilience (VOR), from the view of ecosystem sustainability to describe the holistic condition of a system, in which vigor could be represented by productivity, metabolism, etc.; organization by biodiversity indexes, parameters from network analysis, etc.; and resilience by growth range, recovery time after damage, etc. The VOR indicator system has been generally applied in the assessment of ecosystem health. Taking a broadly compatible approach, Jørgensen et al. (1995) used exergy, structural exergy and ecological buffer capacity to evaluate ecosystem health.

2. Describe the degradation of an ecosystem.—Rapport et al. (1985) used ecosystem distress syndrome (EDS) for expression of an ecosystem in an unhealthy condition. It included specific indicators for description of the decline in nutrient pools, primary productivity, size distribution, and species diversity.

3. Reflect the function and structure of an ecosystem.—Kay and Schneider (1992) used the term “ecosystem integrity” to refer to the ability of an ecosystem to maintain its organization through functional and structural attributes. Karr (1993) used bio-integrity indexes to evaluate aquatic ecosystem health in terms of changes in fish communities in terms of composition and distribution, species abundance, sensitive species, tolerant species, native species and exotic species, etc. Waltner-Toews (1996) emphasized that the choice of evaluation indicators need to be based on functional process,

especially the evaluation of resilience under interference, including integrity, adaptability, and efficiency.

4. Represent sustainability of human-coupled ecosystems.—Rapport (1995) and Fairweather (1999) suggested that ecosystem health evaluation indicators include not only ecological indicators at multiple levels to capture the complexity of an ecosystem, but also biophysical indicators and social-economic indicators to represent the quality and sustainability of ecosystem services provided for human society.

5. Present the goal of natural resources and ecosystem management.—Jørgensen et al. (2011) proposed five criteria: “simple to apply and easily understood by laymen, relevant in the context, scientifically justifiable, quantitative and acceptable in terms of costs, when assessing ecosystem health from a practical environmental management point of view.”

Often, the selected indicators are more or less specific for a given stress or they are applicable only to a particular type of ecosystem or scale. Furthermore, the selection and optimization of ecosystem health indicators should reflect the independence of reference states and be applicable over extensive geographical areas (Jørgensen et al. 2011). The following criteria should be met for selection of the key indicators: (1) sensitive to stresses, (2) simple and easy to apply, (3) strong scientific basis, (4) possible to quantify, (5) anticipatory in responses to stresses, and (6) targeted to the goal of management.

Classification of indicators

Several systematic approaches to classification of indicators are in current usage. The following three are of general applicability.

Classification by the system of “stress, exposure, and response” is used by Jackson et al. (1990). Stressor indicators quantify a natural process, an environmental hazard, or a management action that effects changes in exposure and habitat. Exposure and habitat indicators identify the degree to which a system or its components might experience and respond to the stressor. Response indicators are measured to provide evidence of the biological condition of a resource at the level of organism, population, community, or ecosystem.

Cairns et al. (1993) proposed five groups of indicators for assessment purposes: (1) assessing current condition of the environment in order to judge its adequacy; (2) documenting trends in the condition over time, i.e., degradation or rehabilitation; (3) anticipating hazardous conditions before adverse impact in order to prevent damage; (4) identifying causative agents in order to specify appropriate management action; (5) demonstrating interdependence between indicators to make the assessment process more cost-effectiveness and to reinforce political will to make environmentally sound management decisions. We summarize the major

Table 1. Major principles and characteristics of indicators for different purposes.

Principle and characteristic of indicator	Purpose				
	Assessment	Trends	Early warning	Diagnostic	Linkages
Relevant					
Biological	5	5	3	3	3
Physicochemical	5	5	3	3	3
Social	3	...	3
Stressors					
Sensitive	5	...	5	3	...
Diagnostic	1	1	1	5	1
Quantifiable					
Measureable	3	3	1	3	...
Interpretable	5	5	3	1	1
Acquiring					
Cost-effective	5	...	3
Nondestructive	3	1	1	1	...
Usage					
Broadly applicable	3	3	3	1	1
No duplication	3	5	3
Integrative	3	3	1	1	3
Temporal					
Continuity	3	5	1	1	1
Timeliness	3	3	5	5	3
Spatial					
Appropriate scale	5	5	5	3	3

Notes: Adapted from Cairns (1993: Table 1). Scores are given for each characteristic of indicators, and 1–5 presents the importance of indicators from the least to most; the table may not contain all the indicator features, hence the missing ranks of 2 and 4. Ellipses indicate that, in terms of certain characteristics, these indicators have no or little importance.

principles and characteristics of indicators for different purposes (Table 1), where scores are given for each characteristic of indicators on a scale of 1–5, from least important to most important.

Jørgensen et al. (2011) classified indicators into eight levels from the most reductionist to the most holistic. Level 1 covers the presence or absence of specific species; level 2 uses the ratio between classes of organisms; level 3 is based on concentrations of chemical compounds; level 4 applies concentration of entire trophic levels; level 5 uses process rates, for example primary production; level 6 covers composite indicators (biomass, respiration/production, production/biomass, primary producer/consumer, etc. [Odum 1969]); level 7 encompasses holistic indicators such as resistance, resilience, buffering capacity, size, and connectivity of the ecological network, turnover rate of carbon, nitrogen, and energy, etc.; level 8 are thermodynamic variables, which we may call super holistic indicators, for example, they aim to capture the total image of the ecosystem without inclusion of details—exergy, structure exergy, energy, entropy production, power, mass, and energy system retention time.

None of these systems are ideal, however, as they stand for the practical assessment of ecosystem health. The following biological, physicochemical, and socio-economic indicators are proposed as the three main categories for ecosystem health assessment. Table 2 shows the classification and common indicators of each

category.

For the practical assessment of ecosystem health, we illustrate the following eight kinds of ecosystems, including forests, wetlands, rivers, lakes, estuaries and coastal zones, marine systems, agro-ecosystems, and urban ecosystems, of which the first six are natural ecosystems, though variously affected by human activity, and the last two are human-coupled ecosystems (Table 3).

Because of the complexity of an ecosystem, key species (sometimes termed focal species) are often identified to monitor the comprehensive ecosystem condition. Key species may have a dominant position in a certain ecosystem or are most sensitive to types of stress such as through change in climate or chemical pollution. Key species indicators have been widely used for ecosystem health assessment of forests or rivers, and may also be used in other ecosystems (Table 4).

Integrated indicator system for ecosystem sustainability

Due to limitations of a single-indicator approach for ecosystem health assessment, various attempts have been made to build integrated indicator systems for certain stresses or assessment purposes. Resilience, equilibrium, and equity are three most important characters reflecting ecosystem sustainability.

Table 2. Classification of indicators for ecosystem health assessment.

Classifications	Major indicators
Biological indicators	
Ecosystem level	vigor, organization, resilience
Community level	biomass, productivity, biodiversity, organization structure, trophic structure, relationships within and between species
Population and individual level	individual organization, biochemical reactions, age structure, size structure, natality and mortality, individual growth rate, yield, geographic range
Physicochemical indicators	
Air	air composition, degree of air pollution
Water	water resources, precipitation, level of eutrophication, degree of water pollution, degree of sediment pollution
Soil	physical characteristics, chemical characteristics, soil structure, soil enzyme activity, degree of soil pollution
Socioeconomic indicators	
Human health	mortality rate, incidence of major disease, potential risks to human health arising from environmental factors
Ecosystem services	use of natural resources, conservation of water and soil, recreation and aesthetics, sustainability of services provision
Influence of human activities	industrial emissions, land use, legislation, public participation

Resilience represented by time lag in response and change in ecosystem production

Resilience is measured in terms of an ecosystem’s capacity to rebound structurally and functionally from disturbance. Disturbance (or perturbation) has been central to ecosystem dynamics through evolutionary history, in some instances resulting in a rapid and rejuvenated recovery and in others in degradation and eventual collapse when resilience is exceeded (Vogel 1980, Schlesinger et al. 1990). Both natural and human disturbances are stresses to ecosystems, which in turn may disrupt nutrient cycling, reduce productivity, cause the loss of biodiversity, and lead to other symptoms of ecosystem dysfunctions (Rappport et al. 1985).

“Resilience” is described as the capacity of an ecosystem to recover after dysfunction, while “resistance” is generally described as the capacity of maintaining ecosystem function under stress (Whitford et al. 1999), which could be measured by the survival of

selected species, primary productivity, nutrient cycling, biodiversity, and symbiosis persistence. Measurements of resilience could focus on the recovery rate and degree of those variables measured to evaluate resistance. To quantify resilience (*R*), we use time lag (TL) to express recovery rate and change in ecosystem production (CEP) to express recovery degree

$$R = \frac{CEP}{TL} = \frac{EP_r - EP_d}{T_r - T_d} \tag{1}$$

where *T_r* refers to the time to total recovery; *T_d* stands for the time at which disturbance ended; *EP_r* refers to primary production after ecosystem recovery; *EP_d* refers to primary production while the ecosystem is under disturbance.

At a practical level, the capacity for a system to have resistance and resilience can be tested by applying a perturbation or stress and observing the degree of initial deformation, then subsequent recovery. For example, soil can be exposed in the laboratory to stressors such as

Table 3. Key indicators for different kinds of ecosystems.

Ecosystem types	Key indicators
Forest ecosystem	species-based indicators, diversity, primary production, conservation and restoration indicators
Wetland ecosystem	water-quality indicators, productivity and diversity of phytoplankton and macrophytes, diversity of macro-invertebrates and birds
River ecosystem	species-based indicators, biological indicators of phytobenthos, benthic macroinvertebrates, and fish fauna
Lake ecosystem	diversity of phytoplankton and zooplankton, biomass of phytoplankton and zooplankton, phytoplankton primary production, exergy and structure exergy
Estuaries and coastal zones	species-based indicators, biodiversity, species biomass and abundance, exergy-based indicators, network-analysis-based indicators
Marine ecosystem	habitat indicators, species-based indicators, size-based indicators, trophodynamic indicators, network-analysis-based indicators, food web indicators
Agricultural ecosystem	exergy-based indicators, energy-based indicators, ecological-footprint-based indicators
Urban ecosystem	energy-based indicators, socioeconomic indicators

Note: Adapted from Jørgensen (2011: Chapter 10–18).

Table 4. Key species and measurement indicators for different kinds of ecosystems.

Ecosystem types	Key species	Measurement indicators
Natural ecosystem		
Forests	indicator plants, sensitive plants, specific plants, specific animals, birds, soil animals, soil microbes	composition of flora and fauna; species diversity, biomass; primary production; proportion of exotic species; quantity and quality of habitats; ecosystem-level indices; ecosystem services
Wetlands	indicator plants, sensitive plants, specific plants	same as forests
Rivers	plankton, high-trophic-level fish	species diversity; biomass; primary production; proportion of exotic species; vertical structure and horizontal distribution of species; reproduction and regeneration of species; quantity and quality of habitats; ecosystem level indices; ecosystem services
Lakes	plankton, high-trophic-level fish	same as rivers
Estuaries and coastal zones	plankton, benthic invertebrates, high-trophic-level fish	same as rivers
Marine ecosystems	plankton, benthic invertebrates, high-trophic-level fish	same as rivers
Human-coupled ecosystem		
Agricultural ecosystem	soil animals, soil microbes, plant weed species	species diversity, primary production, ecosystem services
Urban ecosystem	indicator plants, sensitive plants, birds	species diversity, quantity and quality of habitats, ecosystem services

high temperature or heavy metals and indicators of its structure and function observed (Griffiths and Philippot 2013, Griffiths et al. 2008). A function such as ability to decompose organic matter, first decreases following the stress (resistance), then gradually recovers (time lag) but to a degree that may be less than the initial level.

Equilibrium represented by entropy-based indicators

In ecology, “equilibrium” could describe a relatively stable state of an ecosystem during evolution, but is considered to be a “dynamic equilibrium,” because ecosystems are complex dynamic systems. Ecosystem development can be defined as a process in which a variety of biological communities, combined with physical environmental changes, will evolve until the evolutionary climax is achieved. Ecosystems can be viewed as non-isolated systems able to maintain themselves in a far-from-equilibrium condition by exploiting the entropy exchanges with the surrounding environment (Svirezhev 2000, Ludovisi 2014). Therefore, thermodynamics provides an evolutionary appropriate language to describe evolutionary process.

Entropy is a measure of the number of specific ways in which a thermodynamic system may be arranged, commonly understood as a measure of disorder. Since entropy is a state function, the change in the entropy of a system is the same for any process going from a given initial state to a given final state, whether the process is reversible or irreversible. The entropic distance from thermodynamic equilibrium and the entropy exchanges at the ecosystem boundaries are key variables describing the state of ecosystem. In the last decades, a batch of entropy-based indicators have been proposed to describe the stage and orientation of ecosystem develop-

ment, including exergy, structural information, entropy production, specific entropy production and the structure exergy (Table 5).

Among these indicators, the most widely used in ecosystem health assessment are exergy and structure exergy, which focus on the entropic distance from equilibrium and are able to capture the properties and cover the work capacity of an ecosystem. Exergy of an ecosystem accounts mostly for the free energy stored in biomass irrespective of the distribution among ecosystem components, while structure exergy emphasizes the structural differences among ecosystems having equivalent biomass (Jørgensen and Nielsen 1994).

Equity represented by degree of sharing and openness, and change in values of ecosystem services over time

To supply ecosystem services sustainably, an ecosystem needs to remain healthy and to maintain its functions. Valuing the services of an ecosystem’s natural capital can be a useful guide when distinguishing and measuring where trade-offs between human society and the rest of nature are possible and where they can be made to enhance human welfare in a sustainable

Table 5. Entropy-based indicators.

Indicators	Proposed by
Exergy	Jørgensen and Mejer (1979)
Entropy production	Aoki (1989)
Structure exergy (Eco-exergy)	Jørgensen et al. (1994)
Energy dissipation	Kay et al. (1994)
Structural information	Ludovisi (2009)
Net entropy flow	Ludovisi (2012)

Note: Adapted from Ludovisi (2014:Table 1).

manner (Costanza et al. 1997, Farber et al. 2002).

Equity of ecosystem services includes two aspects: space and time. “Space” refers to intragenerational equity of ecosystem services, which are valued by the degree of sharing and openness for access to production in an open market, macro or micro climate regulation, recreational value, culture and aesthetical value, etc. “Time” refers to intergenerational equity of ecosystem services, represented by the change in values of ecosystem services over time

$$V_{\text{change}} = \frac{\text{Value}_2 - \text{Value}_1}{T} \quad (2)$$

where V_{change} refers to the change in values of ecosystem services over time, Value_1 and Value_2 refer to the values of ecosystem services at time 1 and 2, and T refers to the time lag.

In a healthy ecosystem, change in values of ecosystem services over time should be stable, ensuring the sustainability of service provision. There are three conditions for V_{change} : positive, 0, and negative. When V_{change} is 0 or small, one may say that the intergenerational equity of ecosystem services is good and the ecosystem is relatively healthy and sustainable. However, if the increment is large relative to its original condition, it may indicate a long-term degradation and hence weak sustainability. Negative V_{change} represents the loss of intergenerational equity and the sustainability of ecosystem services has been damaged.

Ecosystem Health Assessment Methods

Methods for natural ecosystem

Holistic approach

1. Thermodynamic analysis.—Exergy, a thermodynamic concept, has been applied to ecology since the 1970s. It is defined as the amount of work a system can perform when it is brought to thermodynamic equilibrium with its environment (Jørgensen and Mejer 1977, 1979). Exergy measures the amount of energy needed to break down the ecosystem. Structural exergy is the average exergy per total biomass in the system. With regard to the overall ecosystem health index consisting of system vigor, organization, and resilience (Costanza 1992), exergy can express system vigor and resilience, while structural exergy represents system organization. Given resilience is multidimensional, focal buffer capacities involved in possible stress situations could be introduced to improve the ecosystem health assessment (Jørgensen 1995). Calculations of these indices are introduced in the Appendix: Table A1.

Based on exergy, structural exergy, and buffer capacities, Jørgensen (1995) assessed health states of 15 lake ecosystems. A clear relationship was found between these indicators and lake eutrophication states. Exergy and the first buffer capacity (phosphorus input

as state variable) increase with increased eutrophication, while structural exergy and the other two buffer capacities (temperature and water flow as state variables) increase with the eutrophication up to a maximum value at a certain level of eutrophication above which they will decrease. Xu et al. (1999) investigated freshwater ecosystems stressed by four chemical stresses, acidification, copper, oil, and pesticide contamination with structural, functional, and ecosystem-level indicators. Ecosystem-level indicators included exergy, structural exergy, and zooplankton buffer capacity. The results showed that responses to chemical stress in ecosystem level and in structure and function of the studied ecosystems are highly correlated.

2. Network analysis.—Network analysis extracts comprehensive information on the flow and cycling of matter from mass-balanced flowcharts, including trophic structure and transfer efficiencies, and the organization of the food web (Field et al. 1989, Gaedke 1995). This approach is an important methodology in systems ecology to holistically analyze the complex interactions within an ecosystem (Fath et al. 2007), for it treats the ecosystem as a number of compartments interconnected with each other by flows of energy or matter. Major indicators include total system throughput (TST), ascendancy (A), development capacity (C), average mutual information (I), and Finn’s cycling index (FCI). TST represents the sum of all transfer processes occurring in the system and measures the level of overall system activity. Ascendancy (A) involves ecosystem size and the degree of organization. Development capacity (C) denotes the diversity of the system flows scaled by the total system throughput. Average mutual information (I) represents the average constraint placed upon a single unit of flow in the network. Finn’s cycling index (FCI) is the percentage of all fluxes of biomass that are generated by cycling. Calculations of these indices are introduced in the Appendix: Table A2.

Network analysis can efficiently characterize the vigor and organization of ecosystem. It is used to assess ecosystem health together with thermodynamic analysis. In the evaluation of the micro- and meio-benthic community across the coastal area of the southern Adriatic Sea, Italy, structural exergy, ratio of ascendancy to capacity, and Finn’s cycling index are sensitive to anthropogenic pressure (Vassallo et al. 2006). As a result, these three indicators were proposed as candidate indices for coastal ecosystems health assessment.

Multi-metric approach

Since the 1970s, researchers and managers have realized that monitoring of physical and chemical attributes of water are insufficient for aquatic ecosystem management. Karr (1981) proposed a multi-metric approach, based on an index of biological integrity (IBI) and including a range describing attributes of fish assemblages, to assess the water resource health. IBI integrates

the functional and structural metrics of biological communities. Karr (1981) selected 12 metrics from three categories: species richness and composition, trophic composition, and fish abundance and condition. Data were obtained for each of these metrics and metric values were given with a score of 1, 3, or 5, based on the deviation degree of the test sites from the reference sites (Table 6). Aggregation of the metric scores becomes the IBI measurement for each site.

IBI has subsequently been expanded to other biota, such as invertebrates (Fore et al. 1996), vascular plants (Mack 2007), and algae (Kane et al. 2009) in rivers, streams, lakes, wetlands, and coastal estuaries, and even applied to terrestrial ecosystems (Bradford et al. 1998, Guilfoyle et al. 2009). Generally speaking, representative indicators are selected from each of four major categories: (1) richness measures for diversity of the assemblage; (2) composition measures for identity and dominance; (3) tolerance measures that represent sensitivity to perturbation; and (4) trophic measures for information on feeding strategies and guilds (Barbour et al. 1999). For scoring indicators, alternative methods are developed and widely in use. Bryce et al. (2002) used linear interpolation to place each metric value on a scale of 0 to 10. Mack (2007) converted raw metric values to metric scores (1, 2, 3, and 4) by quadrisecting the 95th percentile of the metric value. In order to better distinguish the degree of impairment, individuals could select the most appropriate method according to the specific situation.

Predictive model approach

A river invertebrate prediction and classification system (RIVPACS) was first proposed and designed for assessment of biological quality of rivers in the UK (Wright et al. 1993). Based on the initial proof of a strong correlation between the environmental features and faunal characteristics of 370 reference sites, RIVPACS utilized a set of physical and chemical data to predict the macroinvertebrate fauna condition (expected) in the absence of stress over a wide range of river types (Wright et al. 1984, Wright 1995). The ratio of the number of macroinvertebrate fauna observed at a test site to the expected taxa number (*O:E* ratio) at reference sites provides a measure of biological impairment, which is a reflection of the ecosystem health states of rivers. The test sites should have similar physical and chemical properties with the reference sites. Based on RIVPACS, the Australian river assessment scheme (AUSRIVAS; Davies et al. 2000) and benthic assessment of sediment (BEAST, Canada; Reynoldson et al. 1995) predictive models were established to assess the ecological conditions of rivers.

Despite the extensive use of the predictive models, one major problem is that these models evaluate freshwater ecosystem health based on the macroinvertebrate assemblage alone, and assume that these species

Table 6. Metrics and scoring criteria of the initial index of biological integrity (IBI).

Category and metric	Scoring criteria		
	5	3	1
Species richness			
Total number of fish species	†	†	†
Species composition			
Number of darter species	†	†	†
Number of sunfish species	†	†	†
Number of sucker species	†	†	†
Number of intolerant species	†	†	†
Green sunfish (%)	<5	5–20	>20
Trophic composition			
Omnivores (%)	<20	20–45	>45
Insectivorous cyprinids (%)	>45	45–20	<20
Piscivores (%)	>5	5–1	<1
Fish abundance			
Number of individuals	†	†	†
Hybrids (%)	0	>0–1	>1
Anomalies (%)	0–2	>2–5	>5

Notes: Modified from Karr et al. (1986) and Roset et al. (2007). Scoring: 5, near reference; 3, moderate deviation from reference; 1, strong deviation from reference.

† Varies with stream order.

reflect all responses of the freshwater ecosystem to stresses. Hence, the predictive models are not applicable when the river is disturbed but the macroinvertebrate community is not affected.

Methods for human-coupled ecosystems

Urban ecosystems and agro-ecosystems are representative of human-coupled ecosystems. They are both natural, social-economic, complex ecosystems and play a crucial role in human life. In this section, methods to assess the health of urban ecosystem and agro-ecosystem are introduced.

First, an appropriate indicator system should be established. For urban ecosystem health assessment, five factors (vigor, structure, resilience, ecosystem service function maintenance, and environmental impact or population health) are mostly considered (Guo et al. 2002, Su et al. 2009). Besides, conceptual models, such as pressure-state-response (PSR; Zeng et al. 2005) and driving-force-pressure-state-exposure-effect-action (DPSEEA; Spiegel et al. 2001) are recommended to organize indicators in a systematic way. For agro-ecosystem health assessment, Vadrevu et al. (2008) considered six factors (biodiversity, soil quality, topography, social organization, farm economics, and land economics), while Zhu et al. (2012) addressed three subsystems (natural ecosystem, social system, and economic system) from four perspectives: vigor, organization, resilience, and equity.

Based on an appropriate indicator system, analytical hierarchy process (AHP) and other mathematical models are used to integrate these indicators.

1. Analytical hierarchy process (AHP) model.—Five steps are included in the AHP (Vadrevu et al. 2008, Zhu et al. 2012): (1) structure the estimation problems into a hierarchical framework; (2) derive models to combine variables on the basis of their relationships with ecosystem health at each level in the hierarchy; (3) examine the consistency of these models; (4) aggregate the data according to the hierarchical model into a single index; (5) assess the results based on the underlying data.

2. Mathematical models.—As for mathematical models, fuzzy synthetic assessment model (Guo et al. 2002, Zhou and Wang 2005), attribute theory model (Yan et al. 2007), and set pair analysis (Su et al. 2009) are introduced to assess urban ecosystem health because of features like fuzziness and multiple attributes. Here we elaborate on the fuzzy synthetic assessment model (Zhou and Wang 2005), which examined the relative health conditions of Beijing from 1996 to 2003.

- 1) Set up the fuzzy set. According to the years and indicators of Beijing urban ecosystem health assessment, three fuzzy sets were set up: the evaluated object set $O = \{1996, 1997, 1998, \dots, 2003\}$; the indicator set $U = \{x_1, x_2, \dots, x_{18}\}$, and the remark set $V = \{\text{healthy, unhealthy}\}$.
- 2) Relative health indicators were divided into two categories, the positive indicators whose value became higher when the urban ecosystem became healthier, and the negative indicators whose value reduced less while the urban ecosystem became healthier. Relative health memberships, u_{hv} of positive indicators were calculated as follows:

$$u_h = \begin{cases} 1 & x = x_{\max} \\ \frac{x - x_{\min}}{x_{\max} - x_{\min}} & x_{\min} < x < x_{\max} \\ 0 & x = x_{\min} \end{cases} \quad (3)$$

Relative health memberships of negative indicators were calculated as follows:

$$u_h = \begin{cases} 1 & x = x_{\min} \\ \frac{x_{\max} - x}{x_{\max} - x_{\min}} & x_{\min} < x < x_{\max} \\ 0 & x = x_{\max} \end{cases} \quad (4)$$

where u_h is health membership of each indicator and x_{\min} and x_{\max} are minimum and maximum value of the indicator x among the assessed years.

- 3) Calculate the relative health membership matrix

$$\mathbf{R}_h = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1j} \\ r_{21} & r_{22} & \dots & r_{2j} \\ \dots & \dots & \dots & \dots \\ r_{i1} & r_{i2} & \dots & r_{ij} \end{bmatrix} \quad (5)$$

in which $r_{ij} = u_h(x)$, $i = 1, 2, \dots, 18$; $j = 1, 2, \dots, 8$.

- 4) Calculate the comprehensive assessment matrix

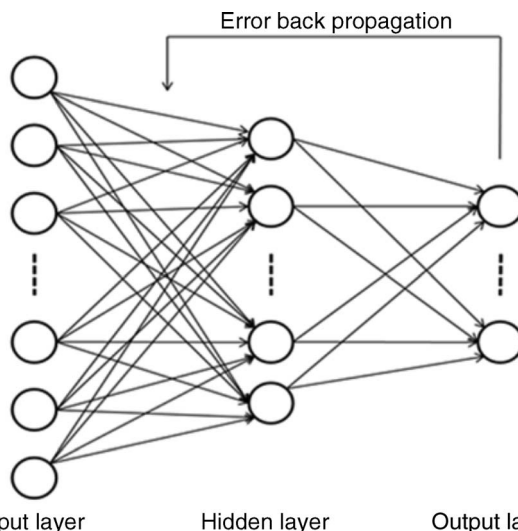


Fig. 1. Schematic illustration of a back-propagation neural network. Vertical dotted lines indicate more neurons in the layer.

$$\mathbf{B} = \mathbf{w} \cdot \mathbf{R}_h \quad (6)$$

where \mathbf{B} is the final urban ecosystem health condition matrix and \mathbf{w} is the weights matrix of indicators.

3. Artificial neural networks.—As computational models based on the structure and function of biological neural networks, artificial neural networks (ANN) are perceived as nonlinear statistical data modeling tools and are capable of tackling complicated problems such as pattern recognition, clustering, classification, and simulation (Araghinejad 2014). There are various types of neural networks, but the most commonly used in ecological modeling is multi-layer, feed-forward, neural networks trained by a back-propagation algorithm such as a back-propagation network (BPN).

A BPN comprises three or more neuron layers, including an input layer, one or more hidden layers and an output layer, with each layer including one or more neurons. Neurons from one layer are connected to all neurons in the adjacent layer, but have no lateral connections within any layer and no feedback connections (Fig. 1). Based on the explicit input and output data, BPN could be trained by comparing the calculated output with the actual output and modifying connection weights to reduce error. A back-propagation network can be used for ecosystem health assessment, with main procedures as shown in Fig. 2.

BPN models have been used to quantify the relationships between habitat variables (input) with specific species assemblages (output), such as macroinvertebrates (Goethals et al. 2007), fish (Tirelli et al. 2009), and diatoms (Philibert et al. 2006). Similar to the predictive models mentioned previously, these BPN models can be

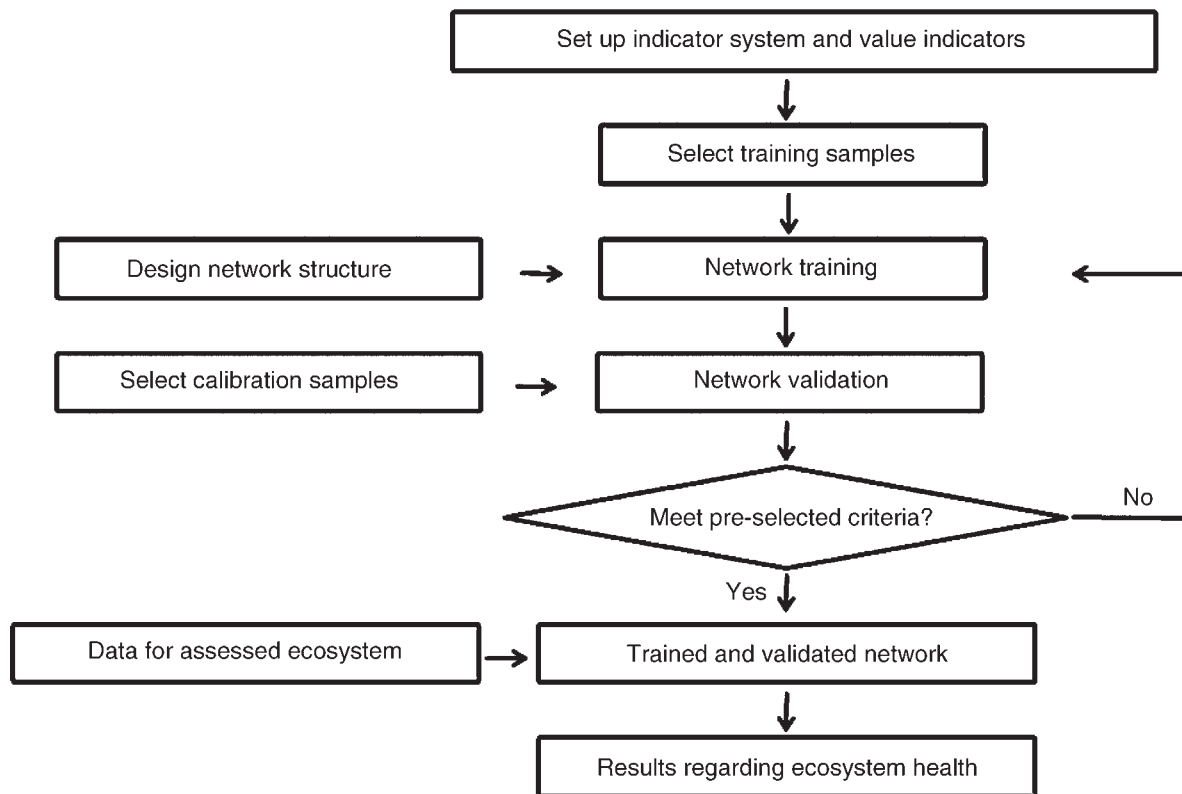


Fig. 2. Procedure for ecosystem health assessment with back-propagation network.

used to assess the change of biological communities and subsequently the health of aquatic ecosystems.

4. Genetic algorithms.—Genetic algorithms (GA) are optimum search techniques inspired by Charles Darwin’s principle of “natural selection and survival of the fittest” (Holland 1975, Goldberg 1989). Similar to the process of population evolution, GA selects fit individuals for reproduction. Three main genetic operators involved in GA are selection, crossover, and mutation. From a population of randomly generated chromosomes, a subset of the fittest chromosomes is selected according to their adaptation and advances towards a new population of chromosomes by crossover and mutation. The procedure is applied iteratively on each population until some preselected criteria are met. GA may be used to choose the most appropriate indicators for predictive models of ecosystem health assessment (D’Heygere et al. 2006, Sadeghi et al. 2013).

In summary, and based on available case studies, we classify the ecosystem health assessment methods in terms of natural or human-coupled ecosystems. However, these methods may be applicable to other types of ecosystem health assessment, which needs to be further confirmed in more applications.

Critical Issues and Perspectives

In our understanding, three critical issues have to be

taken into consideration when assessing ecosystem health. What are the major drivers of change in ecosystem conditions and how do they interact? How can ecosystem sustainability be achieved for the continuous supply of ecosystem services? What resilience strategies should be put in place to allow ecosystems to respond to external stresses?

Drivers

The disturbances or stresses that act as the drivers of change in ecosystems can be broadly categorized as natural and anthropogenic. Natural drivers, like solar radiation, natural climatic variability, and extreme geological activities, exert a significant but one-way influence on ecosystem services, in that they themselves do not get feedback from the ecological changes they cause. In contrast, anthropogenic drivers may result in a wide range of changes to ecosystems, but because people live within or close to the ecosystems they affect, anthropogenic drivers get substantial feedback from ecosystems (Millennium Ecosystem Assessment 2005). The natural and anthropogenic drivers interact over time. For example, the local species loss may initially be the result of anthropogenic influences, but may render an ecosystem more sensitive or more liable to degradation in the face of major events caused by natural drivers. It is the combined effects of several global change stressors that have mobilized major international concern and remediation efforts in recent years (Hooper

et al. 2012). Considering that human welfare depends on ecosystem services (provisioning, regulating, cultural, and supporting), appropriate human intervention in ecosystems and the maintenance of ecosystem health will be a key research topic for the future.

Sustainability

The World Commission on Environment and Development (1987) defined sustainability as “use of the environment and resources to meet the needs of the present without compromising the ability of future generations to meet their needs.” Sustainability has been adopted as the main goal set for many local, national, and international conservation or development efforts. In recent years, social-ecological sustainability has been increasingly recognized in ecosystem stewardship (Chapin et al. 2010). Humans are an integral part of social-ecological systems that can both affect and respond to ecosystem processes, so the synergies and trade-offs between ecological and societal well-being must be addressed when moving efforts towards sustainability (Chapin et al. 2009). In order to maintain and improve the conditions of ecosystem health based on current understanding of the environment with inevitable uncertainty and abrupt change, three strategies should be promoted to foster social-ecological sustainability: control over known anthropogenic stresses, while appropriate intervention is necessary for the health of ecosystems such as forests; pre-emptive actions and policies needed to keep the vitality of ecosystems; and understanding of mutual interactions within social-ecological systems and avoiding or escaping unsustainable social-ecological traps (Cairns et al. 1993, Chapin et al. 2010).

Resilience

The resilience of an ecosystem is one of the three main indicators proposed for assessing ecosystem health and refers to its ability to maintain its structure and function under stress (Costanza and Mageau 1999). In practice, there are two components of resilience, one is resistance and the other is recovery. Given that anthropogenic climate change acts as a key driver of ecosystem change in the 21st century, resistance should be the focus, rather than recovery, as an increasing frequency of extreme climatic events limits the time available for recovery, and the chronic characteristic of climate stressors has also made the role of recovery less effective (Hoegh-Guldberg et al. 2007, Cote and Darling 2010, Darling et al. 2010). Meanwhile, non-climate stressors, like pest disease, pollution, and land use change, will act separately or interactively with climate change. In practice, the selection of resilience indicators must distinguish between resistance and recovery based on both expert consensus and satisfactory empirical evidence (Knudby et al. 2013). Furthermore, in the face of environmental change, resilience, that is the capacity to

revert to the pre-existing state following disturbance, should not be the unquestioned goal of ecosystem stewardship, since change at appropriate times is also necessary for a healthy ecosystem (Julius et al. 2008, 2013).

There are three methods for recovery of ecosystem health: restoration, rehabilitation, and remediation. Restoration involves returning an ecosystem to a high ecological integrity. To do this, rehabilitation is used. Sometimes, due to fundamental changes to ecosystem conditions, the original ecosystem cannot be restored and a new ecosystem will need to be created, and this is remediation (Georges River Catchment 2004). Without the natural or anthropogenic stressors, ecosystems themselves are likely to evolve over time; while in the presence of certain stressors, ecosystems undergo dramatic changes that can alter the ecosystem irreversibly due to the severity of disturbance and degradation or lack of adequate resources, which makes the aims of ecological restoration hard to be achieved. Remediation methods and technologies have been increasingly developed for ecosystem management. The aim of remediation is to create a new ecosystem to replace the original one that cannot be restored because it was either irreversibly damaged or entirely removed, or no reference ecosystem exists to serve as a model for restoration. Considering that remediation technologies are more and more specific to various materials and contaminants (USEPA), remediation practice should be undertaken with adequate knowledge and skills to avoid unnecessary disturbance to the existing species and wildlife habitat values of the ecosystem (Georges River Catchment 2004, Khin et al. 2012).

After more than 20 years discussion and practical applications of ecosystem health, the primary challenge of this field is still the effective integration of ecological understanding with socioeconomic, biophysical, biogeochemical, and public policy dimensions (Rapport et al. 1998, 1999, Waltner-Toews et al. 2003, Depledge and Galloway 2005, Leslie and McLeod 2007, Chapin et al. 2009, Cote and Darling 2010, Costanza 2012, Watters et al. 2013). To address the major challenge, novel approaches are required for ecosystem management. Indicators of VOR that can be sensed remotely or mapped spatially are an essential adjunct to ground-based observations. Tools and models for measuring, valuing, and mapping ecosystem services of value to human society are also required. The combination of indicators of VO&R and ecosystem services using various statistical analysis and models is needed to achieve higher levels of ecosystem management. The measures of sustainability should include three complementary approaches, which are long-term historical analysis, integrated landscape simulation, and microcosm experiments. To avoid the limitations of each of these approaches individually in testing the ecosystem-health-sustainability hypothesis, a combination of these

three would provide a powerful suite of tests (Costanza 2012).

In integrating scales from individuals to the whole systems, small changes can be magnified in multiple ways, potentially through nonlinear interactions, facilitating regime shift and collapse. Thus, maintaining the adaptive capacities and strengthening the resilience of ecosystems by preserving a balance among heterogeneity, modularity, and redundancy is necessary for the sustainable ecosystem services (Levin and Lubchenco 2008). Furthermore, it's important to quantify ecosystem services as natural capital, and incorporate the natural capital into decisions on resource and land use at different scales (Daily et al. 2009). Three key concept components are important: the science of ecosystem production functions and service mapping; the design of appropriate finance, policy, and governance systems; and the art of implementing these in diverse biophysical and social contexts (Daily and Matson 2008). More socioeconomic data are needed to understand human-coupled ecosystem changes (Polasky 2008). Under global change, combinations of decision theory, thresholds, scenarios, and resilience thinking can expand awareness of the potential states and outcomes, as well as of the probabilities and consequences of outcomes under alternative decisions (Polasky et al. 2011). To achieve sustainability cooperation, competition, public goods, and common-pool resources are fundamental features of biological and social systems (Levin 2014). With more concerted efforts and interdisciplinary collaboration, devising workable strategies for ecosystem health towards sustainability can be achieved.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (41371488, 41420104004), the International Scientific Cooperation Program with Grant No. 2012DFA91150), and the Key Research Program of the Chinese Academy of Sciences (No. KZZD-EW-TZ-12).

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Supplemental Material

Ecological Archives

An appendix is available online: <http://dx.doi.org/10.1890/EHS14-0013.1.sm>