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# The Development and Initial Testing of a Quantitative Assessment of Ecosystem Health

Michael T. Mageau, Robert Costanza, and Robert E. Ulanowicz  
University of Maryland Institute for Ecological Economics,  
Center for Environmental and Estuarine Studies, University of Maryland,  
Solomons, MD, USA

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## ABSTRACT

Rapid deterioration of the world's major ecosystems has intensified the need for effective environmental monitoring and the development of operational indicators of ecosystem health. We propose that a healthy ecosystem is one that is sustainable—that is it has the ability to maintain its structure (organization) and function (vigor) over time in the face of external stress (resilience). We then examine methods to quantify these three ecosystem attributes and illustrate how they can be incorporated into a quantitative assessment of ecosystem health. Results from initial test-

ing indicate the potential for evaluating the relative health of similar ecosystems and changes in the health of a single system through time. Microcosm experiments in parallel with simulation modeling will allow us to test the ability of the proposed ecosystem health assessment to quantify the effects of nutrient and toxification stress over a variety of spatial scales. Finally, we discuss the potential for using a modified version of ecosystem health assessment in economic systems and linked ecological economic systems.

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## INTRODUCTION

The concept of ecosystem health is vital to managing our remaining supply of natural capital (Arrow *et al.* 1995). In democratic societies, sound environmental policy depends as much on popular support for policy goals as on good science to specify and provide the means to achieve them. Fortunately, the desirability of preserving ecosystem health is an intelligible goal to lay persons, and public support seems to be increasing along with the intensification of our environmental problems. Global monitoring data indicate a marked deterioration in the condition of the major ecosystems of the world (World Resources Institute 1992; World Watch Institute 1994). Given the rising environmental pressures associated with the exponential increase in global population, effective

monitoring of ecosystem condition is crucial. The U.S. Environmental Protection Agency (EPA) now recognizes the pronounced effect of unhealthy ecosystems on human health and has responded by shifting its goals of monitoring and enforcement activities from protecting only human health to protecting overall ecosystem health (Costanza 1992). Now that ecosystem health has come to the forefront of policy action we are left with the question of what exactly constitutes a healthy ecosystem and the challenge of constructing operational indicators of ecosystem health.

## DIFFICULTIES ASSOCIATED WITH DEFINING ECOSYSTEM HEALTH

The concept of health is difficult to define. It is easier to ascertain the health of a system in terms of the "absence of" rather than the "presence of" certain characteristics. Leopold (1941) contributed to the practice of land health by identifying indi-

Please address correspondence to: Michael T. Mageau,  
University of Maryland Institute for Ecological Economics,  
P.O. Box 38, Solomons, MD 20688.

cators of land sickness. Rapport *et al.* (1985) and Odum (1985) expanded on Leopold's original indicators arriving at what they called ecosystem distress syndrome (EDS). Symptoms of EDS include: reduced biodiversity, loss of nutrient capital, reduction in primary productivity, shifts in biotic composition resulting in increased dominance by exotics and opportunistic "r" selected species, reduced size distribution or increased production per unit biomass, increased amplitude of oscillations of component species and changes in energy flow. In general, an ecosystem is presumed healthy if it displays none of the above symptoms. The fact that so many symptoms of ecosystem distress have been identified, and that there is little agreement regarding the relative importance of each symptom, has made it difficult to arrive at any single definition of ecosystem health.

Costanza (1992) summarized the wide variety of proposed concept definitions of ecosystem health, which are based on the above symptoms of distress: Health as homeostasis; as absence of disease; as diversity or complexity; as stability or resilience; as vigor or scope for growth; and as a balance between system components. Rapport (1995) provided a summary of more specific definitions. Karr *et al.* (1986) stated that a biological system 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. Kerr and Dickey (1984) suggested evaluating ecosystem health using the size distribution of biota. Minns *et al.* (1990) provided a methodology for risk assessment with respect to acidification of Canadian lakes. Schaeffer and Cox (1992) stated that health is achieved when functional ecosystem thresholds are not exceeded. Schindler (1990) provided a detailed account of whole lake acidification experimentation demonstrating a sequence of abnormal signs of ecosystem structure and function. Smol (1992) defined a healthy ecosystem as one that existed prior to human cultural impact. Steedman and Regier (1990) advanced the notion of ecosystem integrity that is evaluated by a suite of indicators of ecosystem breakdown, many of which are similar to symptoms of EDS. Odum (1985) and Ulanowicz (1986) suggested that stressed ecosystems are characterized by an inhibition or even reversal of trends associated with ecosystem development. Costanza (1992) suggested that an ecosystem is healthy if it is stable and sustainable—that is if it is active, maintains its organization and autonomy over

time, and is resilient to stress. The majority of these definitions are based on the effects or impacts of cumulative stress on ecosystems. However, others are based on the source of stress itself and focus on the risks associated with particular stresses (Minns 1992; Suter 1992). In addition, there is also a related body of literature that uses the term "integrity" in place of "health" when referring to ecosystem transformations under stress (Karr 1993; Kay 1993; Woodley *et al.* 1993).

Unfortunately, for each of the above definitions of ecosystem health or integrity there are many methods of measuring or quantifying the particular symptoms of distress, resulting in an inordinate number of ecosystem health indicators. These range from single-species indicators (Kerr and Dickey 1984) to a composite of species (Karr 1991) to measures of biodiversity to system level measures of ecosystem structure, function, and organization (Costanza 1992; Ulanowicz 1986; Schindler 1990) to very broad measures that go beyond the biophysical realm and include human and socioeconomic aspects (Rapport 1992). As one increases the complexity of the indicator, its relevance increases, but the difficulty of measuring and operationalizing the concept increases as well. Costanza (1992) discussed this trade-off between ease of measure and relevance (Figure 1).

Hannon (1992) suggested that it would be advantageous if ecologists could agree on a single indicator of ecosystem health and offered the economists general agreement on gross national product (GNP) as an example. The GNP has its problems, but they could be addressed if the index

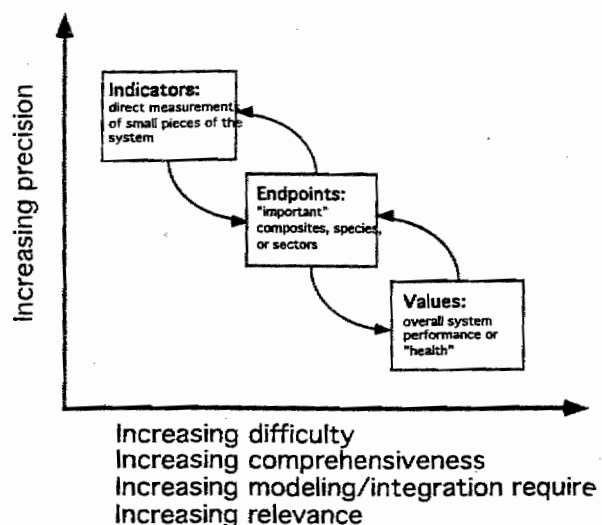


Figure 1. Relationship between indicators, endpoints and values (after Costanza 1992).

was modified concurrent with changing economic conditions (Daly and Cobb 1989). A single indicator, if designed for easy modification through time, could serve the ecologist well. This indicator would have to incorporate as many of the previous concepts as possible while remaining reasonably easy to measure and operationalize. Single-species indices, although inexpensive, easy to measure, and useful for early detection of distress, fall short of these criteria because they give no importance to the other species in the system. Composite-species indices or biodiversity indices are better, but they fail to consider how the components of the system are organized or the pathways of material transfer between components. Finally, value-laden indices incorporating socioeconomic criteria become exceedingly difficult to measure, agree upon, and operationalize. In this paper we propose a systems-level assessment of ecosystem health that is reasonably easy to measure and incorporates values in a general manner allowing for the possibility of reaching a consensus. More specifically, we identify three components of ecosystem health that encompass many of the concepts discussed above, describe the quantification of these components, illustrate how they can be incorporated into a quantitative assessment of ecosystem health that satisfies the above criteria, examine some initial testing of the assessment, discuss the unique opportunities for future testing, and comment on the potential of this assessment method in linked economic and ecological economic systems.

### THREE COMPONENTS OF ECOSYSTEM HEALTH

Costanza (1992) discussed the criteria necessary for a comprehensive, systems-level and operational definition of system health. He summarized the merits and problems associated with several common definitions of system health and concluded that each of these definitions represent important pieces of the puzzle, but no single one adequately serves as the essential operational definition of system health. Costanza (1992) argued that a comprehensive, multiscale, dynamic, hierarchical measure of system vigor (V), organization (O), and resilience (R) is necessary. These concepts are embodied in the term "sustainability," which implies the ability of the system to maintain its structure (organization) and function (vigor) over time in the face of external stress (resilience). This definition of system health is applicable to all complex systems from cells to ecosystems to economic systems and allows for the fact that systems may be growing and developing as a result of both natural and cultural influences. Finally, the time and space frame are obviously important in this definition. Neither individual organisms nor ecosystems are sustainable indefinitely, and the linkages between system longevity and time and space scale is an important part of the problem that is only just beginning to be looked at (Costanza and Patten 1995). Table 1 lays out these three attributes of system health along with related concepts and measurements from various fields.

TABLE 1

Indices of vigor, organization, and resilience in various fields (after Costanza 1992)

Component of Health	Related Concepts	Related Measures	Field of Origin	Probable Method of Solution
Vigor	Function Productivity Throughput	GPP, NPP, GEP GNP Metabolism	Ecology Economics Biology	Measurement
Organization	Structure Biodiversity	Diversity index Average mutual information predictability	Ecology Ecology	Network analysis
Resilience Combinations		Scope for growth Ascendancy	Ecology Ecology	Simulation modeling

GPP = gross primary production; NPP = net primary production; GEP = gross ecosystem product; GNP = gross national product.

The vigor of a system is simply a measure of its activity, metabolism, or primary productivity. Examples include gross primary productivity in ecological systems and gross national product in economic systems. It has been hypothesized that a system's ability to recover from stress, or to utilize it, is related to its overall metabolism, energy flow (Odum 1971), or to its "scope for growth," (Bayne *et al.* 1987) which is the difference between the energy required for system maintenance and the energy available to the system for all purposes. Each of these measures are aimed at the system's capability to respond to generalized stress.

The organization of system refers to the number and diversity of interactions between the components of the system. Measures of organization are affected by the diversity of species and also by the number of pathways of material exchange between each component. For example, a highly organized system is characterized by a high diversity of specialized components and their corresponding specialized exchange pathways. Organization decreases as the diversity of species and the specialization of exchange pathways decrease. It is important to realize that for any given level of species diversity, organization can vary with the pattern of exchange pathways between them. A system containing species that feed on only one or two specific prey items, and are in turn prey for only one or two other species, will have higher values of organization than a system containing the same number of generalist feeders with multiple pathways of exchange between them. Organization, therefore, extends traditional measures of diversity by also considering the patterns of exchange between systems components.

The resilience of a system refers to its ability to maintain its structure and pattern of behavior in the presence of stress (Holling 1986). In the context of this paper, it may refer to the system's ability to maintain its vigor and organization in the presence of stress. A healthy system is one that possesses adequate resilience to survive various small-scale perturbations. The concept of system resilience has three main components. The most commonly used aspect refers to the length of time it takes a system to recover from stress. A second aspect refers to the magnitude of stress from which the system can recover, or the system's specific thresholds for absorbing various stresses. A third aspect has to do with the extent of recovery. A related point involves the alternative system states once thresholds are crossed, these may vary from total system collapse to a stable state that may ac-

tually be more beneficial. The limits of ecosystem stability or resiliences are currently being debated. Holling (1980) argues that the limits range from the assumption of complete global stability, implicit in many of humanity's past efforts to manage, to the idea of ecosystem being extremely fragile.

The three components of system health are illustrated in a three-dimensional plot, and the resulting two-dimensional planes are labeled (Figure 2). The first plane describes systems characterized by various combinations of organization and resilience, but no vigor. Systems with little or no vigor, such as ice, rocks, and minerals, are "crystallized". The second plane describes systems characterized by various combinations of resilience and vigor, but with no organization. Systems with little or no organization, such as nutrient-enriched lakes, streams, and ponds, or early successional ecosystems dominated exclusively by "r" selected species, are eutrophic. The third plane indicates systems that are characterized by various combinations of vigor and organization, but no resilience. Natural variation in external environments preserves resilience preventing systems from reaching the extreme of this plane, but certain highly managed systems, such as agriculture, aquaculture, and plantations, approach this plane and are brittle. Crystallized, eutrophic and brittle systems are not healthy. Instead, a healthy system is characterized by some balance between vigor, organization, and resilience. We propose that a healthy system is one that can maintain an efficient diversity of components and exchange pathways (high organization) while maintaining some redundancy or resilience as insurance against stress, and substantial vigor to quickly recover or utilize stress in a positive manner.

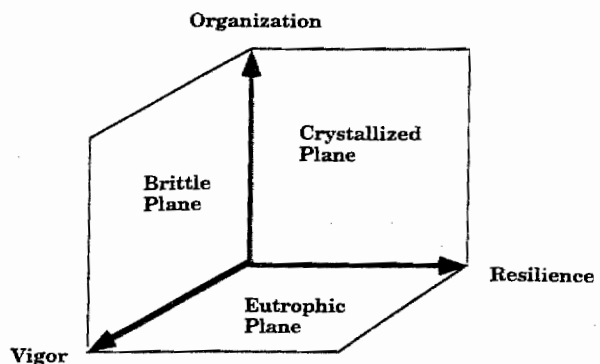


Figure 2. A three-dimensional plot of system vigor, organization, and resilience. The resulting two-dimensional plains are also labeled.

## QUANTIFYING SYSTEM VIGOR, ORGANIZATION, AND RESILIENCE

We have begun to develop and test quantitative measures of systems vigor, organization, and resilience using a combination of mesocosm experiments, simulating modeling, and network analysis. The University of Maryland's Multiscale Experimental Ecosystem Research Center (MEERC) has constructed a series of cosms at several time, space, and complexity scales and is carrying out an integrated experimental and modeling research program aimed at understanding and modeling ecosystems at each of these scales (from microcosms to mesocosms, to small and regional watersheds). MEERC focuses on assessing the response of these systems to nutrient and toxicant stress, and how (and why) these responses change with scale. The ultimate goal of MEERC is to develop and test a set of ecosystem health indicators for these systems, and to develop and test a set of scaling principles that will allow the extrapolation of results across scales. Detailed, dynamic simulation models of all the experimental systems are being developed and the program's experimental design allows the models to be rigorously calibrated and tested. The combined models and experiments allows various indices of vigor, organization, and resilience to be calculated and tested over a range of scales. If these tests are encouraging, then the indices can be formulated into an integrated assessment of ecosystem health that can be applied to large-scale ecosystems, economic systems, and ecological economic systems.

### MEASURING VIGOR

Vigor is the most straightforward of the three components to measure. Vigor can be measured directly and relatively easily in most systems. Examples include Net Primary Production (NPP) in ecological systems, the metabolism of individual organisms, and GNP in economic systems. These empirical measures quantify the magnitude of input (material or energy) available to a system. But as health professionals have long recognized, vigor alone is not an adequate measure of health.

### MEASURING ORGANIZATION

It is more difficult to quantify organization than vigor because quantifying organization involves measuring both the diversity and magnitude of sys-

tem components and the exchange pathways between them. Diversity and multispecies indices fail to incorporate the exchange pathways connecting system components. Network analysis involves the quantitative analysis of interconnections between components of a system (species) and their connections with the larger encapsulating system (their abiotic environments). Practical quantitative analysis of interconnections in complex systems began with the economist Wassily Leontief (1941) using what has come to be known as Input-output (I/O) analysis. These concepts have been applied to the study of interconnections in ecosystems (Hannon 1973, 1976, 1979, 1985a, 1985b, 1985c; Costanza and Neill 1984). Related ideas, under the heading of compartmental analysis, were also developed (Barber *et al.* 1979; Finn 1976; Funderlic and Heath 1971). Walter Isard (1972) was the first to take advantage of the similar methodology by attempting a combined ecological/economic system I/O analysis, and several others have proposed ecological/economic mass-balance models (Daly 1968; Cumberland 1987). Ulanowicz (1986) has used information theory to develop a specialized suite of systems-level, quantitative network analysis indices, which may be used to calculate a system's vigor, organization, and resilience.

Ulanowicz (1986; 1995) describes the quantification of systems-level information indices in detail, so we will provide only a brief summary. The first step in quantifying these indices is to estimate a matrix of material and energy exchanges between system components. Each cell in the matrix carries the label  $T_{ij}$  designating a specific transfer from a particular component in row  $i$  to a particular component in column  $j$ . Estimating matrices of this type for ecosystems is difficult, but with field experiments directed at estimating trophic transfers (such as various tracer experiments and feeding patterns), and improvements in simulation modeling, our abilities are increasing. Once an adequate simulation model is constructed for a system, a complete network of exchanges can be generated for each time step in the model. For example, we are using the simulation models we have calibrated with data from MEERC mesocosm experiments to estimate these matrices of material and energy exchange. The systems-level information indices can then be quantified using the conditional probabilities calculated from these matrices. One can gain valuable insight into ecosystem structure and function by studying the changes in these indices that accompany ecosystem perturbations.

Ulanowicz (1995) identifies mutualism or au-

tocatalysis between system components, connected by cyclic flow, as a nonmechanistic, ecosystem phenomenon that provides evolution and ecological succession with a sense of direction. This natural process dictates the behavior of the system-level information indices. In autocatalysis, an increase in the activity of any component increases the activity of all other members in the cycle and ultimately itself, resulting in configurations that are growth enhancing via positive feedback. These autocatalytic configurations also exert selection pressure on their members. If a more efficient species enters the cycle, its influence on the cycle will be positively reinforced, or if the species is less efficient, negative reinforcement will decrease its role. In addition, as the autocatalytic cycle increases its activity, it adsorbs resources from its surroundings. Therefore, as ecosystems undergo the process of succession in the absence of stress, autocatalysis increases the amount of material being transported throughout the system and the efficiency by which its members transfer material and energy. Finally, different members may come and go, but the fundamental structure of the autocatalytic cycle remains making the loop independent of its constituents. We believe that average mutual information, a systems-level network analysis indice developed by Ulanowicz (1986), may be used as a measure of systems organization. Ulanowicz (1986) argues that autocatalysis streamlines the topology of interconnections in a manner that favors those transfers that more effectively engage in autocatalysis at the expense of those that do not, resulting in networks that tend to become dominated by a few intense flows. For example, as specialists replace generalist in the process of ecological succession each species or system component exchanges material along fewer pathways. Ulanowicz (1995) then describes how these effects can be quantified using a modified average mutual information equation. The statement  $p(a_i, b_j)$  refers to the probability that a unit of energy or material leaves component  $i$  and enters component  $j$  ( $T_{ij}$ ). Because  $T$  is the aggregate of all such system transfers, we can estimate  $p(a_i, b_j)$  by  $T_{ij}/T$ . Similarly,  $p(b_j)$ , the probability that a quantum enters element  $j$ , will be estimated by  $\sum T_{ij}/T$ . Finally, the conditional probability  $p(b_j|a_i)$ , that a quantum enters  $j$  after leaving  $i$  is approximated by  $T_{ij}/\sum T_{ij}$ . Substituting these estimators into the equation for average mutual information yields an equation that quantifies the degree to which autocatalysis has organized or streamlined the systems flow structure.

$$I = \sum T_{ij}/T * \log(T_{ij}*T/T_j*T_i)$$

Ulanowicz (1986) also develops two related concepts. First, he scales the average mutual information equation by the total system throughput (because autocatalysis tends to increase  $T$ ) to yield a network property called system ascendancy ( $A$ ).

$$A = T*I = \sum T_{ij} * \log(T_{ij}*T/T_j*T_i)$$

In addition, average mutual information could be scaled by net input to yield a modified ascendancy value ( $A^*$ ). Ulanowicz (1980) hypothesized that in the absence of major perturbations, autonomous systems tend to evolve in a direction of increasing network ascendancy. First, via an increase in total systems throughput and then via increasing average mutual information as competition for limiting resources begins to streamline the network of system exchanges. The autocatalytic process tends to increase overall system throughput, efficiency, and organization all of which result in increased system ascendancy values. Odum (1969) reached similar conclusions arguing that more developed systems usually contain a larger number of elements that exchange more material and energy among themselves over less equivocal routes. In addition, Odum (1969) found more developed systems tended to internalize or recycle waste products more efficiently decreasing their losses to the external world, and their dependence on imported resources.

Second, Ulanowicz (1986) identifies a third information indice 'system uncertainty' ( $H$ ). This is the upper bound on the total uncertainty if we had no information regarding material exchange. Uncertainty also reflects the total complexity of the system.

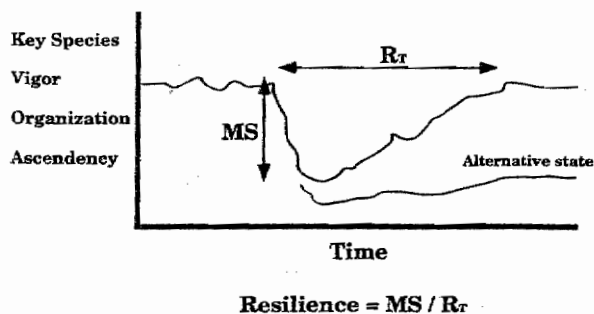
$$H = \sum (T_{ij}/T) * \log (T_{ij}/T)$$

or the total number of potential pathways of material exchange between system components. As natural systems develop, and autocatalysis streamlines the exchange network,  $I$  increases approaching  $H$  as information replaces uncertainty. Ulanowicz then scales  $H$  by total system throughput ( $T$ ) to yield development capacity ( $C$ ), or  $H$  could be scaled by net input to yield a modified capacity ( $C^*$ ). Therefore, with ecosystem development in the absence of perturbation, as  $I$  approaches  $H$ ;  $A$  approaches  $C$ , or  $A^*$  approaches  $C^*$ .

## MEASURING RESILIENCE

Measuring the resilience of a system is difficult because it implies the ability to predict the dynamics of that system under stress. Predicting these ecosystem impacts often requires computer simulation models that represent a synthesis of the best available understanding of the way these complex systems function dynamically (Costanza *et al.* 1990). Figure 3 illustrates two components of resilience that can be estimated using simulation models. The Recovery Time ( $R_T$ ) can be estimated simply by measuring the time it takes for a system to recover from a wide variety of stresses to some previous steady state. The maximum magnitude of stress (MS) from which a system can recover may be measured by progressively increasing simulated stress until the system reverts to some new steady state, and documenting the magnitude of the stress that caused the shift. We propose that an overall measure of resilience can be obtained from the ratio of  $MS/R_T$  (Figure 3). This essentially scales the MS that a system can recover from by the recovery time. Given equal MS, the system with the shortest recovery time is more resilient. Given equal recovery times, the system with the largest MS is more resilient.

When calculating this measure of system resilience the choice of indicators to be tracked over time is very important. The ordinate axis in Figure 3 indicates the candidates for this function. The population of a single species would be easiest to track but would tell us the least about the entire system's response to stress. As discussed earlier, increasingly complicated measures such as those suggested for vigor, organization, and their combina-



**Figure 3.** The two components of resilience and how they are integrated into a single quantitative measure. Candidates for tracking system performance through time are listed on the vertical axis. The lower line indicates the alternative state of a system that was unable to completely recover from stress.

tion (ascendency) will tell us more about the system's response but at the expense of measurement ease and reliability. We are using MEERC experiments and parallel modeling to test these various indices and determine which is best for the purpose of measuring resilience.

Once we obtain a reliable empirical measure of resilience we can test the ability of two indicators to serve as proxies. The first potential proxy for resilience is the ratio of photosynthesis per unit respiration (P/R). This ratio is a measure of the excess vigor or energy available to the system. Our hypothesis is that as this ratio increases, a system has more energy in reserve that will allow it to recover from stress more easily and quickly. To test this hypothesis, we plan to study the correlation between the empirically measured value of resilience and the P/R ratio.

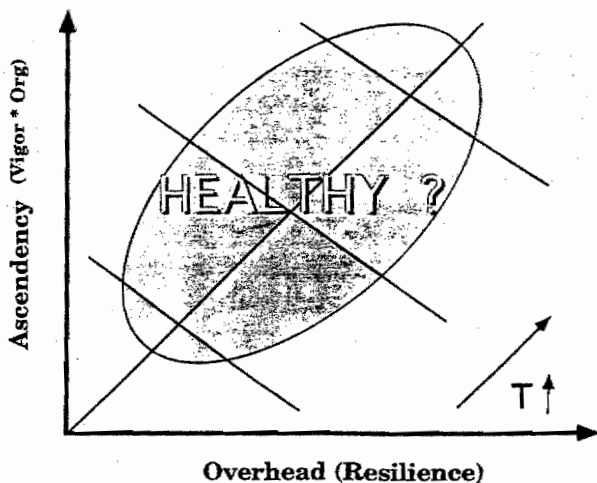
The second potential proxy, Systems Overhead (L), a third information indice developed by Ulanowicz (1986), is calculated as  $C - A$  or  $C^* - A^*$ . Overhead quantifies the number of redundant or alternate pathways of material exchange and may be thought of as a system's ability to absorb stress without dramatic loss of function. Ulanowicz (1986) suggests that higher values of system overhead tend to be associated with systems in earlier stages of development, before autocatalysis has eliminated alternative, redundant, less efficient pathways of material and energy transfer (low L value). Overhead values can also be high in systems containing large seed populations, which have the potential to maintain system vigor and efficiency under different conditions, (an example of high H value). As with the P/R ratio the correlation between systems overhead and our empirical measure of resilience will be determined. If systems overhead can serve as a useful proxy for resilience, we believe network ascendancy and overhead have the potential to provide the ecologist with a method to quantify the change in ecosystem status resulting from anthropogenic and natural stress.

In conclusion, the MEERC experiments and parallel modeling can be used to generate exchange networks representing each of the mesocosm spatial scales. We can then use these exchange networks to calculate Ulanowicz's (1986) system level information indices (T, I, A, C, L) and test their ability to serve as proxies for measuring Costanza's (1992) three main components (V, O, R) of system health. If the initial tests prove unsuccessful, we can test several other potential proxies for V, O, and

R in a similar manner. But if the correlations are strong, we can integrate the indices into a potential assessment of ecosystem health and test its ability to track the health of each experimental ecosystem before, during, and after the nutrient and chemical additions.

## NETWORK ANALYSIS-BASED QUANTITATIVE ASSESSMENT OF ECOSYSTEM HEALTH

In this section we illustrate how ascendancy and overhead can be used to develop a quantitative assessment of ecosystem health. If vigor, organization, and resilience are approximated by net input (or TST), average mutual information (I) and overhead (L), respectively, then the fundamental components of ecosystem health suggested by Costanza (1992) could be quantified given only a systems' network of material exchanges. Taken a step further, ascendancy can be calculated using  $T \cdot I$  (which is equivalent to  $V \cdot O$ ), and resilience can be calculated by  $T \cdot (H - I)$  (which is equivalent to L). Therefore, a quantitative assessment of ecosystem health that depicts a system's ascendancy (vigor\*organization) versus its overhead (resilience) can be constructed (Figure 4). Costanza's (1992) three components of ecosystem health (V,O,R) are embodied in this plot. As the vigor of a system increases, the system is driven out away from the origin. The position of the system in regards to the diagonal depends on the relative ra-



**Figure 4.** A conceptual diagram of the network analysis-based quantitative index of ecosystem health. The healthy region is indicated by the shaded area and represents a balance between system vigor, organization, and resilience.

tio of ascendancy to resilience. A highly ascendent system will plot above the diagonal, and a highly resilient system will plot below the diagonal. As a general hypothesis, we believe that systems with a balance between organization and resilience within a given range of system vigor can be characterized as healthy. In other words, an ecosystem must be free to develop in the absence of serious perturbation to realize its full potential while maintaining adequate resilience to insure against stress, and vigor to quickly recover from small-scale perturbations.

Ulanowicz's (1980) increasing ascendancy hypothesis provides one possible criteria by which a system's trajectory through development may be analyzed. Healthy ecosystems, under this view, are those characterized by unimpeded natural development trajectories. In general, as ecosystems develop following some large-scale perturbation, their characteristic trajectories move along the plot from an area of low ascendancy and high resilience to an area of higher ascendancy and lower resilience. However, these trajectories differ depending on the natural stability of the systems' external environment. All natural environments have some degree of instability, and these natural perturbations will determine the development trajectory of the system. Due to wide fluctuations in the relative stability of natural environments the healthy region is system-specific. For example, estuaries are very dynamic environments relative to the open ocean or to forests. Therefore, the healthy region for estuaries will shift towards the resilient portion of the plot, and that of the open ocean will shift towards the ascendant portion. With a general knowledge of these background natural perturbations, we can quantify the effects of more dramatic anthropogenic perturbations on the development trajectories of health of ecosystems. Thresholds that signal the point at which a system can no longer recover from a perturbation may be determined and used as the boundary for a system's healthy region. Health in this sense relates to the system's sustainability.

### TESTING THE NETWORK ANALYSIS BASED ECOSYSTEM HEALTH ASSESSMENT

Several estimates of ecosystem material and energy exchange networks have begun to appear in the literature (Wulff *et al.* 1989). We initially tested our ecosystem health assessment using exchange networks representing six different estuaries (Wulff & Ulanowicz 1989; Baird & Ulanowicz 1993). The



resulting plot indicates the position of each estuary in regards to its characteristic ascendancy, resilience, and total system throughput (Figure 5). The combined effects of natural and anthropogenic stress on the degree of system development are illustrated by the ecosystem health index plot. For example, the Swartkops and Kromme estuaries have the highest values of total system throughput. The Swartkops is a warm, productive, well-mixed estuary subject to high levels of agricultural and industrial pollution and is, therefore, subject to high levels of both natural and anthropogenic stress, which have hindered its development. The Kromme estuary is also subject to high levels of natural perturbation due to its extremely unstable environment, but it is a relatively pristine estuary, and this may explain its more healthy position on the ecosystem health index plot. Given data sufficient to construct reasonable estimates of exchange networks, comparative plots are a potentially effective way to quantify the relative health of various similar ecosystems (Wulff & Ulanowicz 1989).

Several flow networks have also been generated using simulation model output (Wulff *et al.* 1989). Estimating flow networks using simulation models allows one to study the time series of a system's response to a perturbation and also to study the effects of many different perturbations. Several successive days of network-based indices following the simulated effects of an upwelling event using data from the southern Benguela region (Field *et al.* 1989) is shown in Figure 6. Essentially,

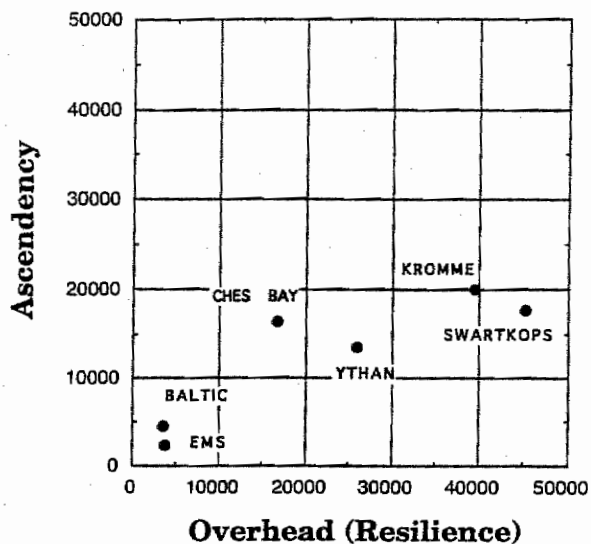


Figure 5. A comparison of the relative positions of six different estuaries using the network analysis-based assessment of ecosystem health.

this plot illustrates the successional development trajectory of an open-ocean plankton community recovering from a natural perturbation. According to Field *et al.* (1989), the upwelling event provides a pulse of nitrogen and flushes most members of the plankton community out of the system. In the initial days of the simulation, the pulse of phytoplankton growth and associated increase in total system throughput both begin to decline causing a dramatic decrease in ascendancy relative to that for resilience. But, as time progresses, and nitrogen limitation increases, the rate of decline in ascendancy decreases and that for resilience increases as competition for limiting nitrogen increases system efficiency. By the 18th day following the upwelling event, the simulated system has returned to a condition characterized by high ascendancy, low resilience, and low total system throughput—exactly what you might expect for a highly efficient, nutrient limited, open ocean, plankton community.

We plan to use MEERC experiments and parallel modeling to further test the health assessment. We will use the calibrated model output to estimate flow networks for the ecosystems representing the various spatial scales. We will then calculate the various system level information indices, and construct a time series plot or trajectory for each of the five different sized mesocosms. Each trajectory will consist of ten points marking five day intervals for the entire experimental duration. The resulting plots will be compared, and the relative health of each mesocosm will be quantified. The working hypothesis, as indicated in Figure 7, is that the smaller mesocosms will be less healthy

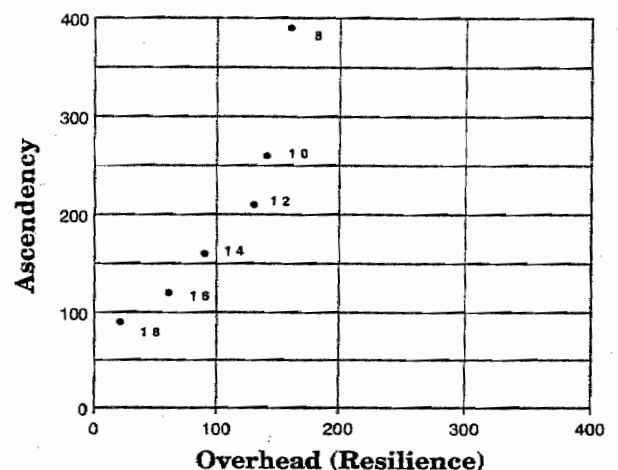
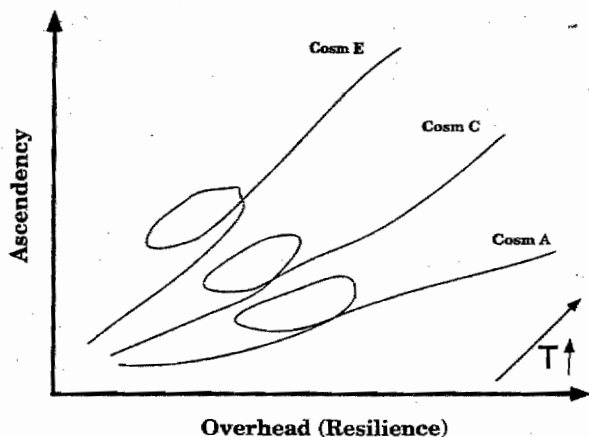


Figure 6. A comparison of the relative position of an open-ocean plankton community various days after an upwelling event using the network analysis-based assessment of ecosystem health.



**Figure 7.** The predicted trajectories of the MEERC benthic/pelagic mesocosms using the network analysis-based assessment of ecosystem health.

(in terms of restricted development) and more adversely affected by the stress associated with the nutrient pulse. We believe the ecosystem health assessment plot will capture any differences between mesocosm trajectories, and that these differences will be quantified statistically.

## QUANTIFYING THE HEALTH OF ECONOMIC SYSTEMS

It is a relatively easy step from matrices of material exchange in ecosystems to the I/O matrices used to analyze exchange pathways in economic systems. Therefore, our proposed index of ecosystem health may also be used to ascertain the health of economic systems in a more comprehensive way than currently popular methods. For example, the GNP has traditionally been (mis)used as an index of economic health and human welfare. Essentially, GNP is a measure of market activity that adds up all production without differentiating between costs and benefits. There are severe environmental and social problems with using GNP as a measure of economic health and human welfare. GNP ignores nature's contribution to production and the costs associated with environmental degradation. This often leads to over exploitation of natural resources and excessive reductions in environmental assimilation capacity. Costanza (1991) provides an example of this phenomena using a standing forest. The forest provides real economic services such as conserving soil, cleaning air and water, providing habitat for wildlife, and supporting recreational activities. But, as GNP is currently

calculated, only the value of harvested timber is figured in the total. So, if we harvest our forests for economically valuable timber, but ignore the costs of lost ecosystem services we are likely to over-harvest. Therefore, continued economic growth, although increasing GNP, may entail greater costs than benefits and lead to reductions in human welfare and economic health.

Daly (1993) makes an interesting analogy between economic change and ecological succession similar to that outlined above. Early successional ecosystems are characterized by a high production efficiency (expressed as a high P/B ratio), whereas mature ecosystems are characterized by a high maintenance efficiency (expressed as a high B/P ratio). Odum (1969) noticed that young ecosystems tend to maximize production, growth, and quantity, whereas mature ecosystems tend to maximize protection, stability, and quality. For the young system, the flow of production is the quantitative source of growth and is maximized, but for the mature system the flow of production is the maintenance cost of protecting the stability and quality of the stock, and is minimized.

Daly (1993) suggests that the evolution of human economy can be explained in similar fashion. He argues that we must make the transition from a young growth-oriented economic system to a mature economic system characterized by development—not growth. In other words, the economies, like ecosystems, must first grow by increasing throughput, and then once limits are approached, growth must be replaced by development as a means of increasing human welfare. The GNP may have served as a useful indicator of economic health in the growth-oriented phase, but it is misleading in the more mature developmental phase. The indices discussed above (T, I, A\*, L and C\*) may be useful in quantifying both growth and development in economic systems, and may guide the transition from young growth economies to more mature development economies.

If we begin with an I/O table of the U.S. economy we can calculate net input (T\*) the same way we do for ecosystems. This is similar to GNP, but with the accounting boundaries drawn to include government and households as endogenous sectors (Costanza 1980). Calculating I, A\*, O and C\* can also be done the same way we do for ecosystems, but with slightly different interpretations. If our goal is a mature developed economy, coupled with increasing human welfare (A\* must increase), then we must maintain throughput (T\*) at a constant level, while increasing economic develop-

ment or efficiency (as measured by I). This means we must stabilize our input of natural resources, internalize or recycle more of our economic waste, and increase the efficiency by which we add value within the production process. The degree to which we are successful in doing this can be quantified by calculating and tracking the values of T, I, and A\* over time. Finally, given some fixed capacity (C\*), A\* should not increase beyond some optimal limit. We can maintain the resilience of our economic system by insuring the presence of some redundancy (as quantified by overhead) in our production process to absorb likely changes in the global economy and environment.

### TESTING THE INDICES OF ECONOMIC HEALTH

The indices of economic health need to be tested. One could begin by analyzing a time series of I/O tables of the U.S. economy and track the ability of these indices to accurately quantify changes in economic growth and development. We hypothesize that certain periods, such as the years following the energy crisis, would be characterized by slight increases in economic organization (I) and that the indices could capture these differences. It would also be interesting to examine the relationship between economic growth rate (T) and organization (I) throughout economic history. Finally, we would like to study the behavior of T, I, and A\* in the years before and after the late 1960s. Daly and Cobb (1989) suggested that GNP may have begun to fail as an indicator of economic health and human welfare in the late 1960s because this period may have marked the point at which we should have begun our transition from the young growth economy to the mature development phase.

### CONCLUSIONS

It is clear that the indices presented in this paper are in an early stage of development, but they are potentially testable, and their use may entail large rewards. We have presented some preliminary applications and a strategy for testing the indices in a multiscale experimental research environment.

All indicators have their problems, but ones that are capable of measuring the three general system characteristics of vigor, organization, and resilience would be useful in assessing the status and health of both ecological and economic sys-

tems. Applied to ecological systems they could help to guide management decisions to ones that are ultimately more sustainable. Applied to economic systems they would be an extremely helpful guide in choosing the policies necessary to ease the difficult transition from the young growth-oriented economy to the mature development-oriented economy.

Finally, if these indices can be used to assess the health of ecological and economic systems independently, then they should also be capable of assessing the health of combined ecological economic systems. Achieving the goal of sustainability requires the ability to deal with linked ecological economic systems over a broad range of space and time scales. One important strength of the indicators, which we have developed, is that they are general enough to apply to *all* systems, regardless of space and time scale. Further experimental testing of the indices (using, among other things, the MEERC multicosts) will ultimately determine their utility for this purpose.

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