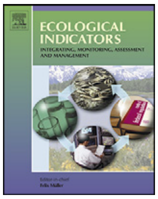
Ecological Indicators 11 (2011) 1185–1190

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Emergy-based complexity measures in natural and social systems

S. Ulgiati[a,*], M. Ascione[a], A. Zucaro[a], L. Campanella[b]

[a] Department of Sciences for the Environment, "Parthenope" University of Napoli, Italy
[b] Department of Chemistry, University of Roma 1 "La Sapienza", Roma, Italy

ARTICLE INFO

Article history:
Received 2 July 2010
Received in revised form
29 December 2010
Accepted 30 December 2010

Keywords:
Emergy
Complexity
Diversity
Urban systems

ABSTRACT

A complexity indicator based on the diversity of energy and resource uses by a system is proposed in this paper. The indicator is an emergy-based index of complexity derived from a modified Shannon information formula that provides a quantitative assessment of the diversity of sources. The emergy approach assigns to each driving input a weight that derives from the environmental work performed by nature in order to generate such resource. This quality assessment goes far beyond the simple accounting of mass and energy of input flows, but takes into proper account their interlinkage with the biosphere dynamics. The rationale of the proposed indicator is that complexity cannot be assessed by simply counting individuals, species and processes, but requires that focus is placed on several aspects of resource flows, namely their amount, frequency, and quality. Different mixes of emergy input flows originate different levels of growth and complexity. Systems that only rely on a small set of sources out of the large number potentially available possess a built-in fragility, that may determine their collapse in times of shrinking or changing resource basis. For validation purpose, the proposed indicator was applied to the performance of selected national economies (Nicaragua, Latvia, Denmark and Italy) in selected years and of the urban system of Roma (Italy) over a forty-year (1962–2002) historical series. Results point out an increasing complexity of the urban system of Rome over time, while a lower complexity was calculated for the investigated national systems as a whole (likely effect of nationwide averaging), with Italy ranking highest and Latvia lowest. The same assessment performed for the Italian agricultural system over a twenty-year time series (1985–2006) shows a decline of the emergy-adjusted Shannon indicator from about 75% down to 62%, while the decline was from 73% to 63% for the agriculture of Campania region (southern Italy).

1. Introduction: state-of-the-art and innovative measures of diversity

Complexity of systems has long been represented by "information-theory" measures. For example, complexity in bits is the number of yes–no decisions required to define a configuration and is expressed on a logarithmic scale. In short, the information-theory measures the logarithm of the possibilities among the parts and connections. For example, there is great complexity at the small-scales of molecules and heat, where information-theory measure on a logarithmic scale is molecular entropy. However, information theory measures do not differentiate between large scale complexity that operates a macroscopic natural or social system and small scale complexity with the same number of parts that have smaller influence on the global dynamics of the larger system in which they are embedded. Information-theory measures do not distinguish this complexity on small molecular scale from that found on a large ecological scale. The awareness of such a limit gave rise to innovative measures, all based on Shannon information formula and all trying to overcome the scale problem by means of concepts that incorporate time and spatial scales into the assessment. Two of such different measures are reviewed in the following.

1.1. Diversity in ecosystems

While studying the interactions between components of ecosystems, Margalef (1968) suggested that "a measure of the aggregation of the ecosystems may be found in the average distance between the place of energy input and the energy sink. The distance can probably be measured either in terms of space or of time". He also pointed out that "there is some energy exchange between. . .subsystems in the sense that the less-organized subsystem gives energy to the more-organized, and, in the process of exchange, some information in the less-organized is destroyed and some information is gained by the already more-organized". The transfer of energy between subsystems originates a hierarchical organization of components, where many components at the lower

---

* Corresponding author. Tel.: +39 0577 234232; fax: +39 0577 234254.
E-mail address: sergio.ulgiati@uniparthenope.it (S. Ulgiati).

1470-160X/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ecolind.2010.12.021

levels 'pay the bill' of supporting few components at the higher ones. Finally, Margalef compared an ecosystem to a message transmitted by means of a certain code. Borrowing expressions from information theory, he defined the average information content per individual as

$$D = -\sum p_i \log_2 p_i = \frac{1}{N} \log_2 \left[\frac{N!}{N_a! N_b!, \ldots, N_s!} \right] \tag{1}$$

where N_a, N_b, ..., N_s are number of individuals of species a, b, ..., s; N is the total number of individuals; p_i is the probability that one individual belongs to species i. The minimum of these expressions is when all individuals belong to the same species, while the maximum is when each individual belongs to a different species. These cases are both improbable in nature, while actual values are in between: Margalef called this measure "diversity" and discussed it as a measure of organization, correlating it with the size of the sample, the energy flow per unit biomass and the entropy production in sustaining a unit of biomass in the ecosystem. Changes in diversity have been discussed by Margalef as useful and clear indicators of movement of the ecosystem back and forth on the succession pathway.

1.2. Thermodynamic depth

Lloyd and Pagels (1988) developed a measure of complexity named thermodynamic depth, based on a probabilistic metric in information theory. The author's concern was to avoid a definition of complexity based on additive properties of the individual objects. If so, complexity could be increased just by increasing the number of the objects, thus making complexity to proliferate very cheaply. Rather, "complexity must be a function of the process...that brought the object into existence...Seven bulls need not be too much more complex than one bull. It took billion of years for the earth to evolve one bull; but one bull and a few compliant cows will produce seven bulls relatively speedily" (Lloyd and Pagels, op. cit.). Given a macroscopic state, d, of a system D that can be reached through n different trajectories, experiments can assign a probability p_i to the i-th trajectory. A trajectory of macroscopic states of a system D is defined as an ordered set of macroscopic states $a_i, b_j, \ldots, c_k$, such that D has been measured to be in the state a_i at time t_1, in the state b_j at time $t_2 \geq t_1$, ..., in the state c_k at time $t_n \geq t_{n-1}$. Lloyd and Pagels proved that the complexity of the state d, that has been reached through the i-th possible trajectory, is measured by the function

$$D(d) = -k \ln P_i \tag{2}$$

and that the average complexity of a state is proportional to the Shannon entropy of the set of trajectories that can lead to that state,

$$S = -k \sum p_i \ln p_i \tag{3}$$

where k is an arbitrary constant. They named depth the function $D(d)$ and defined complexity as the pathway from the reference state to the present one. Considering all the possible trajectories that may lead to the present system's state, they calculate the so-called thermodynamic depth D_T of a state, as the amount of entropy that the system has pumped from the 'relevant' degrees of freedom (those that needed to be constrained for the system to evolve into the state d) to 'irrelevant' degrees of freedom (the remaining ones) in the course of constructing the state d. The thermodynamic depth can be shown to be "proportional to the amount of information needed to identify the trajectory that leads to d given the information that the system is in d already" (Lloyd and Pagels, op. cit.):

$$D_T(d) = (k_B \ln 2)\,[I_o(d) - I(d)] \tag{4}$$

In other words, the depth as a measure of system's complexity is greater when the trajectory leading to the state d is unlikely or when the number of discarded trajectories is higher.

2. Incorporating quality and hierarchies within complexity measures

The diversity and thermodynamic depth indices developed by Margalef and by Lloyd and Pagels address the important issue of complexity from an information theory and probabilistic point of view, by looking at the organization and the development trajectories of a system's state, which is already a major step ahead in complexity assessment. Brown et al. (2006) and Brown and Cohen (2007), building on Odum's emergy synthesis approach (Odum, 1996) identified a main problem in the lack for an overall measure of biodiversity at various levels of an ecological hierarchy, due to the fact that Shannon-like diversity measures cannot be summed. If they were summed – these authors point out – bacteria and other small animals and plants would dominate the resulting diversity to the total neglect of the larger species. What is needed is to develop a quantitative evaluation of total biodiversity within regions or ecosystems by weighting biodiversity at each hierarchical level by means of trophic-level quality indicators (identified as "transformities") derived from the emergy approach. In this way measures of biodiversity can be quantitatively compared and changes resulting from species loss can be scaled based on transformities. A more realistic picture of total biodiversity emerges and allows comparison of losses and gains that result from changes in ecological health.

2.1. Emergy and transformity: concepts and definitions

Odum (1996) introduced the concept of emergy in order to account for the quality of incoming energy and resources, i.e., for the environmental services supporting a process as well as for their convergence through a chain of energy and matter transformations in both space and time. By definition, emergy is the amount of energy of one type (usually solar) that is directly or indirectly required to provide a given flow or storage of energy or matter. Solar emergy is expressed in solar equivalent joules (seJ, or solar emjoules). The solar emergy required to generate a unit flow or a storage of available energy is called solar transformity and is expressed as solar emergy joules per joule of output flow or product (seJ/J). The transformity of solar radiation is assumed equal to one by definition (1.0 seJ/J), while the transformities of all the other flows and storages (including those related to human societies) are calculated based on their convergence patterns through the biosphere hierarchy.

While it is true that all energy can be converted to heat, it is not true that one form of energy is substitutable for another in all situations. For instance, plants cannot substitute fossil fuel for sunlight in photosynthetic production, nor can humans substitute sunlight energy for food or water. It should be obvious that a characteristics that makes an energy flow usable by one set of transformation processes makes it unusable for another set. Thus, quality is related to a form of energy and to its concentration; where higher quality is somewhat synonymous with higher concentration of energy and results in greater flexibility. So, wood is more concentrated than detritus, coal more concentrated than wood, and electricity more concentrated than coal. As a consequence, the quality (concentration, wave-length, pulsing, etc.) of incoming energy makes it able to drive different forms of complexity in recipient systems. The emergy approach makes the quality assessment possible and provides concepts and quantitative calculation procedures rooted in systems ecology and irreversible thermodynamics.