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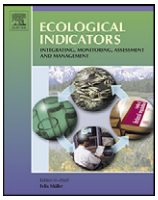

Building a systemic environmental monitoring and indicators for sustainability: What has the ecological network approach to offer?☆

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ABSTRACT

The development of systemic environmental monitoring and indicators for sustainability requires one to tackle the complexity of human–environmental systems. To this end the ecosystem approach is proposed here as a framework and the ecological network analysis as a tool for investigation while an urban system, represented as a water flow network, is discussed as a case study. Flow distribution is used to calculate total system throughput, development capacity, average mutual information, ascendency and overhead. These indices condense the complexity of the flow structure (representing system's metabolism) into a few measures that provide information on how systems grow and develop; because of this they are consistent with the sustainability context.

Two alternative scenarios are presented to discuss the effects of management actions (policies) on sustainability as they change the flow structure and system level indices. While it is shown that increasing system activity (intensity of processes) augments potential for development but not realized development, actions that improve the organization of flows, thus increasing average mutual information, may reduce total system throughput and drive the system toward more sustainable conditions.

System level indices are holistic measures that unveil the relation between internal processes and whole system performance. Understanding this relation is crucial because the former are the target of environmental policies but sustainability, the objective of such policies, is an overall system trait. Because of these features system level indices can be examples of a new quality of indicators for sustainability assessment.

1. Introduction

It is common wisdom that the transition toward sustainability implies taking action at the social, economic and environmental level (Gallopin, 2003; Redclift, 1987). Such transition, however, is made difficult by the inherent complexity of these domains: variables are many and interactions produce complicated dynamics with feedbacks (Parrot, 2010; Pickett et al., 2001). The interrelations between variables of different nature make this intricacy even harder to unravel: our perception of cause and effects is confounded (Levins, 1995; Holling, 1986), with consequences on planning and policy making.

In this scenario systemic approaches to sustainability that cope with complex, simultaneous interactions of different nature in a trans-disciplinary way have been called for (Ojima et al., 1994; Kay et al., 1999), while current practice still roots in mono-disciplinary studies that in the environmental domain focus on water quality and quantity, soils degradation, land fragmentation and so forth. The hope is that single sector policies increase the environmental performance of systems and their combined effects may favor sustainability, which on the other hand is difficult to assess due to the lack of measuring systems for such an elusive trait (Fricker, 1998).

Sustainability is a complex feature that implies multiple dimensionality, but that also pertains to the system as a whole; it is an overall attribute that emerges from the internal processes that characterize human–environmental systems. Multidimensionality and wholeness are two features that make the search for indicator systems to monitor sustainability very difficult.

The OECD (1993) introduced the Driving Force–Pressure–State–Impact–Response (DPSIR) model to tackle the difficulties inherent in the multiple dimension of environmental problems. Rather than a true model it is a framework in which indicators are used to

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substantiate cause and effect mechanisms of environmental problems and response action. By manipulating single-issue indicators aggregate indices can be obtained that reveal patterns of environmental performance at the whole system scale (Clerici and Bodini, 2004).

Single metrics to assess sustainability are not many. The most popular one is the ecological footprint (Fricker, 1998; Wackernagel and Rees, 1996). Despite its several limitations and the partial view it offers of sustainability (Scotti et al., 2008), it is a good example of how the multiple dimensionality (i.e. many single-issue metrics) can converge to an overall index pertaining to sustainability.

Coping with the whole system dimension represents the new challenge for the development of effective sustainability monitoring systems and according to this any approach in this direction should imply (Wiggering et al., 2010):

- the use of systemic models both as conceptual bases and description of real systems;
- the development of holistic measurement concepts as prerequisites for a new generation of indicators;
- that focal goals and targets that determine the evaluation procedures referring to the indicator systems have to be holistic.

The ecosystem approach has much to offer in this respect. This paper intends to provide an example of its potential through a case study that considers a human settlement as focus of analysis. The city environment is an appropriate target for this type of investigation because it has much in common with the ecosystem, as witnessed by the vast literature on the subject (Alberti, 2008; Newman, 1999; Tjallingii, 1993). Also, because of the preponderance of human-driven processes cities are the natural domain to which the discourse on sustainability applies.

In this paper an urban system is described using flow networks, models that view the system as a suite of exchange flows between its component parts. These models are investigated using the apparatus of network analysis. This methodology has largely supported the study of natural ecosystems (Bondavalli et al., 2006; Christian et al., 2005; Heymans et al., 2002; Baird and Ulanowicz, 1989) and can be applied in the context of this paper as it satisfies the requirements listed above. In fact: (1) flow networks are systemic models as they capture in a unique scheme most (sometimes all) the components and their interactions in a system by focusing on their macroscopic outcomes, the exchange flows of a certain currency; (2) indices obtained from the analysis of flows are holistic by their very nature because they summarize in a few metrics all the information and complexities hidden in the flows articulation of a system; (3) the flow structure is the expression of a unitary (holistic) process of growth and development (Ulanowicz, 1997) that becomes the focal goal and target for the evaluation through system level indices.

The present application intends to show: (a) how the complexity of human systems can be captured by the ecosystem approach and which indicators can be obtained to describe these systems in their whole properties and (b) what system level indices of network analysis can tell us about sustainability while measuring growth and development. The overall objective is to contribute toward creating a plausible monitoring framework that cope with systems' complexities, and to discuss what it can add to a new generation of monitoring systems and a new quality of indicators.

2. Methods

2.1. Description: the system as a flow network

The system under investigation is a small municipality, known as Sarmato, that belongs to the province of Piacenza, located in the Emilia Romagna region (northern Italy). It extends over 26.96 km^2 and sustains a population of 2583 inhabitants. The entire municipal area is the unit of investigation: it comprises a more densely populated core and the agricultural surroundings.

Industrial activity counts as many as 45 enterprises, including a power plant, a sugar processing firm, a centre for organic waste composting and several plastic and metal firms.

Intensive agriculture is also developed, with 41 farms spread across the municipal area. The main products are corn (30% of the entire production), soybean (20%), sugar beet (20%) and tomatoes (10%). A high number of enterprises (58) are linked in various ways to the building sector: commerce activities comprise 59 units while 30 ventures provide various services (for public and social use and to enterprises).

This system has been described as a water flow network. Water has been chosen due to its dominance in mass budgets and importance to humans, as it cannot be surrogated or substituted. To represent water exchanges in the municipality of Sarmato, decisions first were taken as to what the elements of the network had to be. The final list of components (label, name and explanation) includes:

1. Wells: for water withdrawal.
2. Water distribution system (WDS): a public enterprise that distributes water to the entire municipality.
3. Industry: a compartment which groups all of the industrial activities.
4. Families and commerce: accounting for water used by families and commerce activities.
5. Power plant: an oil burning 250 MW plant that produces electricity.
6. Agriculture: all water uses necessary to sustain the intensive agriculture that dominates in the area.
7. Public services: schools, hospital, swimming pools and other sports facilities.
8. Aquaculture: a farm where various fish species are raised.
9. Streams: it includes all the water bodies flowing throughout the municipal area (channels and streams).
10. Purification system: treatment facilities for wastewaters before discharge.

A finer resolution of the networks (i.e. considering different types of industrial activities as separate compartments) was not possible due to the lack of the necessary detailed information. Once the main components of the network were defined, all types of flow had to be identified and quantified. Their values, in m^3 year^{-1}, are given in Fig. 1 (upper graph), which depicts the water network of Sarmato.

The network is a yearly snapshot of the system. No net accumulation or loss of water occurs in the system, so that the assumption that the system and its compartments are in a steady state (inflows that balance with the outflows), as required by the network analysis (Ulanowicz, 1986) holds. In many cases the values for fluxes were estimated using data provided by the municipality offices, the chamber of commerce, and collected from various environmental reports and technical documentation supplied by the Regional Agency for Environmental Protection (ARPA). An explanation of the procedure used for flow quantification is given in Appendix A.

An alternative scenario for water use (Fig. 1, lower graph) can be hypothesized considering aquaculture, power plant,