Ecological Modelling 258 (2013) 1–8

Contents lists available at SciVerse ScienceDirect

Ecological Modelling

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

Thermodynamics-based categorization of ecosystems in a socio-ecological context

Luca Coscieme[a], Federico M. Pulselli[a,*], Sven E. Jørgensen[b], Simone Bastianoni[a], Nadia Marchettini[a]

[a] Department of Physical, Earth and Environmental Sciences, University of Siena, via della Diana 2/A, 53100 Siena, Italy
[b] Copenhagen University, University Park 2, 2100 Copenhagen Ø, Denmark

ARTICLE INFO

Article history:
Received 14 January 2013
Received in revised form 22 February 2013
Accepted 23 February 2013
Available online 30 March 2013

Keywords:
Ecosystems
Input-state-output
Emergy
Ecosystem services
Eco-exergy
Socio-ecological systems

ABSTRACT

Ecosystems can be viewed as thermodynamic systems, open to energy and matter, that self-organize towards higher complexity and organization, create order, and self-maintain far from thermodynamic equilibrium. Ecological systems are closely interrelated (in a landscape and in the biosphere) and with human systems, such as urban systems or, generically, economic systems. These relations have been summarized and measured by the concept of ecosystem services and the definition of socio-ecological systems. In order to detect ecosystem properties and dynamics in this context, it is recommended to use "super-holistic" indicators, e.g. thermodynamic indicators such as emergy and eco-exergy. Emergy accounts for energy and matter inputs converging to a system, while eco-exergy is a state-based descriptor of a system's structure based on biomass and genetic information. The characteristics of a generic ecosystem can be described by the relationship among the three orientors – emergy, eco-exergy, ecosystem services – making it clear that inputs are used up, directly or indirectly, to create and maintain a given system state and/or to produce services in output. This paper presents an input-state-output description of ecosystems in a socio-ecological context which leads to a characterization in 8 categories, in order to provide a new contribution to systems ecology.

1. Introduction

Ecological systems self-regulate, showing a tendency toward low entropy (high exergy) configurations, building gradients and order from thermodynamic equilibrium (disorder) (see Prigogine, 1980; Tiezzi, 2006; Jørgensen, 2012; Pulselli et al., 2010). The primary role of humans in shaping the environment implies that, nowadays, ecosystems are effectively the environmental part of coupled socio-ecological systems (SESs) (or human-environmental systems), with specific behaviors and, consequently, a specific evolution (Berkes and Folke, 1998; Müller and Kroll, 2011).

SESs, defined as "systems of bio-geo-physical and social factors in interaction, at several spatial, temporal, and organizational scales" (Redman et al., 2004) show, in fact, specific emergent properties which can be investigated by developing holistic measurement concepts as prerequisites for a new generation of indicators (Bodini, 2012; Fath et al., 2001).

The complex nature of socio-ecological relations actually precludes a reductionist approach (Glaser et al., 2008), implying a systems perspective and transdisciplinary analysis, in order to understand the dynamics of non-pristine ecosystems (see Pulselli et al., 2008; Zurlini et al., 2006).

The variables that link ecosystems and human components have been summarized by the widely used concept of ecosystem services, applicable for a wide range of ecosystems: from those relatively undisturbed, to landscapes with mixed patterns of human use, to ecosystems intensively managed and modified by humans (De Groot, 1987; Costanza et al., 1997; MA, 2005).

In this paper the ecosystem service concept is used, together with thermodynamics-based indicators, in order to categorize ecosystems in a socio-ecological context, and provide a new contribution to systems ecology.

2. Methods

Generically, ecosystems work on energy and matter inputs coming from the environment, reach a particular configuration of changing components which define their state, and provide different outputs for different "users". The dynamic interactions among these components structure the system and its functions. When considering an ecosystem as a component of an SES, once the functions are known, the nature and magnitude of value to human

* Corresponding author. Tel.: +39 0577232087; fax: +39 0577232004.
E-mail addresses: fpulselli@unisi.it, federico.pulselli@unisi.it (F.M. Pulselli).

0304-3800/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ecolmodel.2013.02.031

society can be analyzed and assessed through the goods and services provided by the functional aspects of the ecosystem (De Groot et al., 2002).

An input-state-output scheme for systems (Pulselli et al., 2011), such as that presented in Fig. 1, is used in this paper to describe ecosystems in a socio-ecological context, using three different indicators (emergy for input accounting, eco-exergy for state description, and ecosystem services for output evaluation).

Emergy (Odum, 1996), is an indicator able to identify the convergence of matter and energy into a system on a common basis (e.g. solar energy), enabling us to quantify and weigh the inputs that feed the system during its evolution (Odum, 2000; Odum et al., 2000). It is not a state function, because it depends on the kinds of energy and the process to build a given state of the system. Operatively, emergy is calculated using suitable unit emergy values (UEVs) to convert different flows of energy (and matter) into equivalent solar energy (Odum, 1996). UEV represents, in fact, the position of one energy form in the thermodynamic hierarchy of energy transformations in the biosphere, starting from solar energy. The total emergy of a system (Em_s) is given by the sum of the energy content (E_i) of the ith input to the system multiplied by the corresponding UEV (Fig. 1) (for a deeper view of emergy calculation and algebra, see Bastianoni et al., 2011).

For pristine ecosystems the continuous increase of emergy is an indicator of a proper evolution towards a mature system (climax stage), self-perpetuating and in equilibrium with the physical habitat (Cai et al., 2004; Campbell, 2001; Fath et al., 2001; Odum, 1971, 1988). For example, Burkhard et al. (2011) show the continuous increase of emergy along an ecological succession for a protected forest.

However, in SESs, where natural systems interact with human systems and dynamics, the increase of emergy (as a consequence of increasing inputs that reach the ecosystem) is not always "good" in the sense that it will support the evolution of the system towards a climax stage (see, for example, Tilley and Swank, 2003; Vassallo et al., 2009). In fact, a portion of the inputs that the ecosystem receives is not used to build structures in order to maintain the non-equilibrium state (e.g., excess of nutrient, pollutants, etc.). Consequently, when studying SESs and the novel ecosystems that are now appearing (Prach and Walker, 2011), we need to consider the emergy flow to the ecosystem together with an indicator able to show if different inputs are used to structure the system and increase its diversity, maintaining its creativity, intended as work capacity (i.e., eco-exergy, among others).

Eco-exergy is a measure of complexity in ecology, as expected to be associated with the presence of more complex organisms, which, in principle, correspond to higher information content (in the form of DNA, RNA, and protein sequences) and greater distance from thermodynamic equilibrium (Jørgensen and Mejer, 1979, 1981; Jørgensen, 2008; Marques and Nielsen, 1998).

Combined in a ratio, these holistic indicators (eco-exergy to emergy flow ratio) allow us to understand if the system under study is globally following a path that will take it to a "better" or to a "worse" state (as already investigated by Bastianoni and Marchettini, 1997; Bastianoni, 2006, 2008; Bastianoni et al., 2005, 2006; Pulselli et al., 2010). Briefly, when an ecosystem is relatively young and acquires new inputs, the eco-exergy to emergy flow ratio tends to be lower; when the system is developing toward the climax stage, the ratio tends to rise.

However, when considering SESs, the evolution of the ecosystem toward a "better" or "worse" state must also be intended from an anthropocentric perspective, i.e. including the ecosystem's development and health (see Müller and Leupelt, 1998), as well as the ecosystem's utility for humans. Ecosystems help secure the conditions that allow our survival, moderating weather; stabilizing soil, coastlines, and climate; influencing our atmosphere; and making it possible for humans to exist and persist in general (Levin, 1999). The ecosystem service values can be used as an indicator of the useful outputs provided by nature, when we consider ecosystems as submerged in a socio-economic context (Costanza et al., 1997; MA, 2005; TEEB, 2010).

In fact, ecosystem services are defined as "the benefits people obtain from ecosystems" (MA, 2005). These benefits can be viewed as "ecological functions of value to humans" (Fisher et al., 2009). They depend on functions and biodiversity (Balmford et al., 2008; Braat and ten Brink, 2008; Dobson et al., 2006; Loreau, 2010; Luck et al., 2003; Naeem, 1998; Peterson et al., 2009; Turner et al., 2008) but also on users' needs (TEEB, 2010). The overall ecosystem services basket includes an ecosystem's organization (structure), operation (process), and outflows, if they are consumed or utilized by humans either directly or indirectly (Boyd and Banzhaf, 2007).

The anthropocentric viewpoint, intrinsic to the ecosystem services concept, implies that the quantification of natural services is made by means of environmental economic methodologies (De Groot et al., 2002). The inclusion of an indicator expressed in "economic" terms opens our approach towards extra-ecological systems (see Odum and Odum, 2000). A similar approach is needed to build "a common conceptual framework of the social and environmental fields" (Ostrom, 2009).

Since the MA (2005), a quite rigid classification of ecosystem services in four categories has been widely accepted, including *provisioning services* (i.e. food, water, timber, fiber etc), *regulating services* (that affect climate, floods, disease, wastes, water quality etc), *cultural services* (that provide recreational, aesthetic, and spiritual benefits), and *supporting services* (i.e. soil formation, photosynthesis, nutrient cycling etc). Each of these categories raises different problems of data availability, data processing, and services evaluation, influencing the analysis.

To achieve sustainable development, the human use of an ecosystem (as a sub-system of a socio-ecological system) should be optimized without damaging it (the ecosystems approach, in CBD, 2005; see also Shepherd, 2004; Bodini, 2012). Jørgensen and Nielsen (2012) stated that a complete diagnosis, focused on the ecosystem services, could be developed by the use of complementary indicators such as emergy and eco-exergy.

3. Thermodynamics-based characterization of ecosystems in a socio-ecological context

The joint use of thermodynamic indicators and ecosystem services seems to be promising in detecting ecosystem properties and interactions with the anthropic sphere. This research line is relatively new, but it has already provided some interesting results. In general, different ecosystems have a very different translation capacity of emergy (inputs) into eco-exergy (structure, organization), as well as of eco-exergy into ecosystem services (outputs). For example, high eco-exergy to emergy flow ratios describes ecosystem characterized by a great efficiency in transforming available inputs (as emergy) into structure and ecosystem organization (as eco-exergy).

Bastianoni et al. (2006) showed how the eco-exergy to emergy flow ratio assumes higher values for "older" ecosystems, suggesting a dependency of this ratio on the age of the system.

Jørgensen (2010) connects a system's structure and organization description (with eco-exergy) with a user-side approach (ecosystem services), highlighting a relation between a biophysical and an economic evaluation of the environment. The author classifies the ecosystems investigated into five classes (from A to E), according to how much of the potential ecosystem services they provide (estimated from work capacity) are used by humans. The first class (A) includes the ecosystems which are utilized most by man for a series