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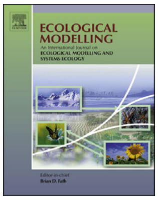

Environmental accounting for ecosystem conservation: Linking societal and ecosystem metabolisms

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ABSTRACT

This paper proposes an approach to environmental accounting useful for studying the feasibility of socio-economic systems in relation to the external constraints posed by ecological compatibility. The approach is based on a multi-scale analysis of the metabolic pattern of ecosystems and societies and it provides an integrated characterization of the resulting interaction. The text starts with a theoretical part explaining (i) the implicit epistemological revolution implied by the notion of ecosystem metabolism and the fund-flow model developed by Georgescu-Roegen applied to environmental accounting, and (ii) the potentials of this approach to create indicators to assess ecological integrity and environmental impacts. This revolution also makes it possible to carry out a multi-scale integrated assessment of ecosystem and societal metabolisms at the territorial level. In the second part, two applications of this approach using an indicator of the negentropic cost show the possibility to characterize in quantitative and qualitative terms degrees of alteration (crop cultivation, tree plantations) for different biomes (tropical and boreal forests). Also, a case study for land use scenarios has been included. The proposed approach represents an integrated multi-scale tool for the analysis of nature conservation scenarios and strategies.

1. Introduction

According to the results of the Millennium Ecosystem Assessment project, the increase in well-being experienced by part of the human population in the last 60 years has been achieved at the cost of the most extensive and rapid transformation of ecosystems in human history (Millennium Assessment, 2005). This explosion human activity on the planet has led some authors to propose the introduction of two concepts: (i) a new geological era called *Anthropocene* (Crutzen and Stoermer, 2000; Lewis and Maslin, 2015; Steffen et al., 2015a, 2011) to stress that currently biophysical processes controlled by humans represent the main driving force behind changes in the ecosystems (Zalasiewicz et al., 2008); and (ii) the notion of *planetary boundaries*, i.e., ecological limits for the human activity in order to operate safely within a global change framework (Rockström et al., 2009; Steffen et al., 2015b). The concept of planetary limits clashes with the economic strategy of perpetual growth, and implies acknowledging that the reproduction of the societal structures and functions depends on the integrity of ecological processes. In particular, two factors determine these limits to economic growth: its dependence on the availability of natural resources (limits of the supply capacity) and the damage that socio-economic activities implies on nature (limits of the sink capacity). For this reason, in the last decades there has been an increasing interest in developing approaches to improve the analysis of both the dependence and the impact of humans on ecosystems.

The ongoing effort to build an international framework on *environmental accounting* can be interpreted as a result of this interest (EEA, 2011; Obst, 2015; UN, 2014a,b,c; World Bank, 2010). This framework has the challenge to standardize the organization and presentation of useful information for characterizing the interface between the economy and the environment in order to support decision making (Vardon et al., 2016). In practical terms, this new System of Environmental Accounts is expected to complement the current System of National Accounts (UN, 2014a). This goal is approached by using two categories to define the elements describing socio-economic patterns in relation to nature: stocks of people and artefacts, and flows of energy and materials.

However, the ecosystem accounting framework developed continues to be labeled as "experimental", indicating that no complete agreement has been reached on how to carry out such a task (Bartelmus, 2015, 2014; UN, 2014b). The distinction proposed between stocks and flows have created many ambiguities when

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applied to multiple-scales analysis since the criteria used for defining these categories blur if non-equivalent descriptive domains and multiple boundaries are considered simultaneously (Giampietro and Lomas, 2014; Mayumi and Giampietro, 2014). Furthermore, the complex nature of the two systems analyzed implied that the methodologies proposed did not result completely satisfactory. Methodologies based on economic variables are in some cases effective in focusing on monetary benefits obtained by people exploiting ecosystems. However, they are not as effective in assessing the changes that this exploitation causes. On the other hand, methodologies based on biophysical indicators are effective in focusing on quantitative and qualitative changes suffered by ecosystems, but not as effective in assessing the consequences on the economy and the social well-being.

This dilemma points at a systemic conundrum of integrated assessment. To deal with this conundrum, it is very useful to frame the analysis of sustainability issues adopting the notion of *metabolism*. This concept assumes by default the co-existence of different relevant scales and dimensions of analysis (Giampietro, 2014; Giampietro et al., 2012). Thus, it becomes possible to characterize the reproduction of human societies by a continuous flow of energy and materials taken from and discarded to the environment, i.e. societal metabolism (Cottrell, 1955; White, 1943; Zipf, 1941). In the last decades, societal metabolism has been gaining momentum with the search for consistent environmental accounting methods for sustainability (Fischer-Kowalski, 1998a,b; Giampietro, 2014, 1997, 1994; Giampietro et al., 1997; González de Molina and Toledo, 2014; Padovan, 2000).

An important contribution to this field has been provided by the *Bioeconomics* framework (Georgescu-Roegen, 1971; Giampietro et al., 2012; Mayumi, 2001). The bioeconomic framework moves the attention away from an input/output analysis of the various flows of goods and services consumed and produced to an analysis of *funds*, or the reproduction of production factors. This distinction between flows (inputs/outputs) and funds (estructural elements) makes it possible to explictitly address the issue of scale that appears when environmental boundary conditions are considered.

The aim of this paper is to present Multi-Scale Integrated Assessment of Societal and Ecosystem Metabolism (MuSIASEM) (Giampietro, 2004; Giampietro et al., 2013, 2012), based on the flow-fund model of Georgescu-Roegen, as an approach to make integrated assessments of society and nature. To this purpose, the theoretical basis for the concept of ecosystem metabolism, and the potentials of this approach to produce integrate assessments of the societal and ecosystem metabolisms are explained in section 2. To exemplify this potential, section 3 illustrates the reproduction of biomass as a fund, and section 4 presents three examples of application of this approach aimed at generating a quantitative assessment of the alteration level for terrestrial ecosystems: tree plantations, crop cultivation, and a hypothetical case study with different scenarios of land uses.

2. Theoretical basis

2.1. Ecosystem metabolism

Building on Lotka (1925), the ecologists E.P. Odum and H.T. Odum developed a methodological approach capable of generating quantitative analysis associated with the notion of *ecosystem metabolism* (Odum, 1957, 1956), becoming one of the most influential concepts in Systems ecology (Jørgensen, 2012). The general theoretical framework makes it possible a biophysical accounting of energy flows through networks, called *energy chains* (Odum, 1975). Energy chains define the relationships between different components making up an ecosystem, labeled as different *energy forms* (Odum, 1971; Odum and Odum, 1976). Ecosystems are represented in *energy flow diagrams* by using symbols carrying out specific meanings (Brown, 2004; Odum, 1994, 1983, 1971), as illustrated in Fig. 1.

The key feature of this approach is the possibility of integrating in quantitative terms information referring to different scales, whose identity is derived from the existing knowledge of ecosystems. This method makes it possible to establish a bridge between the metabolic characteristics of specific energy forms, observable at different levels of analysis. Thus, the characteristics of functional compartments (e.g. herbivores) at a meso level, can be linked to the characteristics of individual species of herbivores describing structural elements expressing the function (e.g. rabbits and dears) at a lower level of analysis. In the same way, functional elements representing the meso level can be linked to the characteristics of the whole ecosystem at the macro level. The ability of establishing these bridges across levels is important because the characteristics of emergent properties of the whole network (Odum, 1985, 1969; Odum et al., 1995) are observable only at the whole ecosystem level interacting with its context. This potential represents a remarkable feature of this accounting system, capable of handling the quantitative representation energy forms that are non-equivalent and non-reducible to each other using conventional mathematical models.

It must be noticed that this approach has been developed by using some of the most innovative scientific concepts of their time, in particular non-equilibrium thermodynamics applied to the ecological complex self-organizing systems (Glansdorff and Prigogine, 1971; Maturana and Varela, 1980; Nicolis and Prigogine, 1977; Schneider and Kay, 1994). The simultaneous adoption of thermodynamic and ecological narratives has some epistemological implications and assumptions. The thermodynamic narrative is used to describe the characteristics of the whole ecosystem, whose parts and functions are described using physical laws and conventional thermodynamic analysis. The ecological narrative is based on the assumption that biological and ecological processes of autopoiesis are taking place inside the system and are capable of stabilizing the identity of biological and ecological types at a local scale. It implies that the information stored in biological and ecological systems is reproduced and effectively used to maintain the expected characteristics of the functional and structural elements within the network, i.e. a given identity for metabolic elements, determining what should be considered as negative entropy for them. The concept of negative entropy (Schrödinger, 1967; page 78) makes it possible establish a link between the thermodynamic and ecological narrative. In fact, the definition given by Schrödinger refers to what is required from the environment by living (metabolic) systems. Thermodynamic constraints mandate a compatibility between internal processes of metabolism and the external processes determining the boundary conditions.

The simultaneous validity of these two narratives implies an impredicative relation (circular causality) between processes taking place at the same time at different scales: the metabolic characteristics of the parts (structural elements) determine the viability of the metabolic characteristics of the functional elements (bottom-up causation); and the metabolic characteristics associated with the required functions determine the feasibility of the metabolic characteristics of the structural elements (top-down causation). This is a well-known characteristic of complex systems organized over hierarchical levels (Giampietro, 1994; Pattee, 1973; Simon, 1962) called also holarchy (Koestler, 1969), double asymmetry (Grene, 1969) or equipollence (Iberall et al., 1980). The need to simultaneously describe metabolic processes at different space-time scales makes impossible to define a clear and unique boundary for the various elements, constraining the analyst to select a specific *environmental window of attention* (Odum, 1996, 1971). This